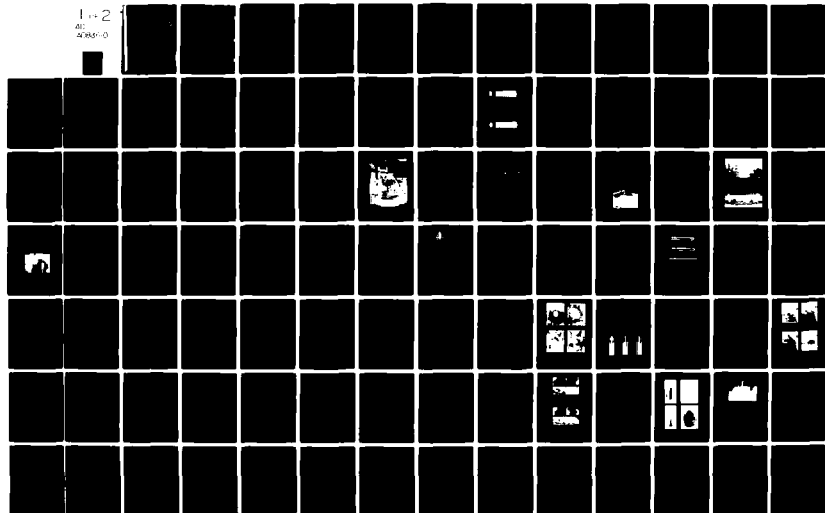


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DEVELOPMENT OF ARMY FIRE-RESISTANT DIESEL FUEL

INTERIM REPORT
AFLRL No. 111

by

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APR 23 1980

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U. S. Army Fuels and Lubricants Research Laboratory
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San Antonio, Texas

and

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U. S. Army Mobility Equipment Research
and Development Command
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Six different approaches to achieving reduced fuel fire vulnerability investigated by the U.S. Army have been described. The last approach was selected for developing fire-resistant fuels (FRF) for diesel-powered ground equipment. The selected approach involves the inclusion of emulsified water in surfactant-stabilized diesel fuel. An alternative approach, using half as much water and trace amounts of antimist agent in surfactant-stabilized diesel fuel, also has been investigated. Screening studies followed by		

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20. ABSTRACT (Cont'd)

laboratory, bench-scale, and full-scale experimental investigations have led to the development of clear-to-hazy fire-resistant microemulsions of 10 vol% water and 6 vol% surfactant (FRF-A) and alternatively, of 5 vol% water and 3 vol% surfactant with 0.2 wt% antimist agent (FRF-B), both formulated in DF-2 diesel fuel. The surfactant comprises a mixture of reaction products formed from two moles of diethanolamine and one mole of oleic acid, or 1.009 moles of oleic acid in a modified version of the surfactant.

Flammability evaluations demonstrate that these aqueous microemulsions yield diminished mist flammability while either eliminating pool burning or providing rapid self-extinguishment of pool fires, even at fuel temperatures more than 10°C above the base fuel flash point. Bench-scale ballistic tests, using 20-mm high-explosive incendiary tracer projectiles, and full-scale ballistic tests, using 3.2-inch precision shaped charges, confirm and correlate with the flammability data.

Diesel engine and turbine combustor performance tests have been conducted in which no difficulties were encountered in starting, idling, and running on FRF-A formulations under typical operating conditions. As would be expected from the water content, relative to the base fuel case, higher total fuel flow rates are required to produce equivalent power. However, in diesel engines, full power can be generated with these microemulsions simply by adjustment of maximum fuel rate settings.

Performance of these fuel formulations has been evaluated in several different laboratory single-cylinder and multicylinder engines without alteration of injection timing, injection duration settings, or compression ratio. Also, successful 250-hour endurance tests have been conducted in a single-cylinder version of the 12-cylinder AVDS-1790-2C M60 tank engine. Results of these tests indicate that, depending upon the specific engine and its operating conditions, work cycle efficiencies may remain about the same or increase somewhat when FRF formulations are used. Diesel engine exhaust measurements indicate increases in unburned hydrocarbons, no change or increases in carbon monoxide, no change or decrease in nitrogen oxides, and no change or decreases in particulate and smoke. Similar measurements on the gas turbine combustor exhaust gases indicate reduced temperatures, increased unburned hydrocarbons, increased carbon monoxide, and decreases or no change in smoke.

The antimist agent in FRF-B formulations caused higher than normal pressure drops in diesel engine filters and prevented efficient atomization in turbine combustor nozzles. Moreover, FRF-B formulations experienced substantial degradation in fire resistance in diesel engine fuel recycle systems. On the other hand, FRF-A formulations were not degraded when recycled and caused no filtration or atomization problems.

FOREWORD

This report was prepared at the U.S. Army Fuels and Lubricants Research Laboratory (AFLRL), Southwest Research Institute, under DoD Contract Nos. DAAK70-78-C-0001 and DAAK70-80-C-0001. The project was administered by the Fuels and Lubricants Division, U.S. Army Mobility Equipment Research and Development Command (MERADCOM), Fort Belvoir, Virginia 22060, with Mr. F.W. Schaekel, DRDME-GL, serving as Contracting Officer's Representative. The loan of a 20-mm rifle and the provision of a supply of 20-mm high-explosive incendiary tracer ammunition was arranged by the Project Manager--Vehicle Rapid Fire Weapon Systems, Rock Island Arsenal at the request of the Fuels and Lubricants Division of the U.S. Army Mobility Equipment Research and Development Command (MERADCOM). This report covers the period of performance from 1 October 1977 to 31 December 1979.

Acknowledgement is given to Mr. W.W. Wimer for participation in the canvass of emulsifying agent manufacturers and suppliers, to Dr. R.J. Mannheimer for participating in the canvass and screening of antimist agents, to Messrs. J.H. Frazar, S. Nail, and E. Nieves-Marcano for conducting laboratory preparations and experiments; to Messrs. M.R. Burgamy, J. Kachich, and J.P. Pierce for conducting ballistic and back-up flammability experiments; and to Messrs. D.C. Babcock and L.D. Sievers for supervising laboratory and engine tests. Special acknowledgement is given to Messrs. M.E. LePera, R.D. Quillian, Jr., A.A. Johnston, S.J. Lestz, and F.M. Newman for their participation, encouragement, and suggestions. Acknowledgement is given to Mr. J.W. Pryor for editorial assistance in producing this report. Portions of this report were presented at the Society of Automotive Engineers Fuels and Lubricants Meeting, Houston, TX, 2-4 October 1979 and published as SAE Paper No. 790926.

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I. INTRODUCTION

The U.S. armed forces and the transportation industry have a continuing need for fire safety fuel for ground vehicles and aircraft. Such fuel would reduce the threat of fire to vehicles as well as to personnel. An optimum fire safety fuel would achieve such fire-hazard reductions without creating adverse effects upon vehicle or engine performance. Toward this end, the U.S. Army and other Government agencies have been conducting research on fire-resistant fuels (FRF) for over a decade. This report documents the early Army studies and presents experimental results obtained during the period 1 October 1977 to 31 December 1979 on the Army's current sixth-generation, fire-resistant fuel--the one which offers the most promise yet for successful field application.

II. BACKGROUND

A. Prior Modified Fuel Research by U.S. Army

The six generations of fire-resistant fuels which have been investigated by the Army are summarized in Table 1. The Army's initial efforts toward development of a fire-resistant fuel comprised studies of techniques for the irreversible rapid solidification (gellation) of fuels for rotary wing aircraft.^{(1,2)*} This approach was soon altered to consider the use of second-generation modified fuels throughout the flight profile. Such studies investigated semirigid, but pumpable, high-internal-phase-ratio aqueous emulsions of military jet fuels, JP-4, JP-8, and JP-5, and commercial jet fuel, Jet A-1.^(3,4) These fuel-in-water emulsions appeared solid-like until subjected to shear stresses which exceeded their yield strength.^(3,4) Viscous-liquid, high-internal-phase-ratio aqueous emulsions made up the third generation of Army fire-resistant fuel compositions. These were prepared from low-volatility aircraft fuels, JP-5, JP-8, and Jet A-1.⁽⁴⁾ Beginning in 1971, the fourth generation fuels in the Army's modified fuel research program comprised dilute solutions of polymeric antimist agents in low-volatility jet fuels, JP-5, JP-8, and Jet A-1. These extremely high molecular weight polymers

* Superscript numbers in parentheses refer to the list of references at the end of this report.

TABLE 1. SIX GENERATIONS OF FIRE-RESISTANT FUEL FORMULATIONS
INVESTIGATED BY THE U.S. ARMY

1. Fuel gellation just prior to hazard occurrence (Initiated by U.S. Army Aviation Material Laboratories--1964-1966).
2. Semisolid, but pumpable, fuel-in-water emulsions (Initiated by U.S. Army Aviation Material Laboratories--1965-1970).
3. Viscous-liquid, fuel-in-water emulsions (Initiated by U.S. Army Coating and Chemical Laboratories--1969-1972).
4. High molecular weight polymeric additives for inhibition of mist formation (Initiated by U.S. Army Coating and Chemical Laboratories--1971 →)
5. Volatile halogenated fire suppressant as fuel constituent (Initiated by U.S. Army Ballistic Research Laboratories--1972-1976).
6. Current, nonviscous, water-in-fuel, fire-resistant fuel (FRF) emulsions (Initiated by Fuels and Lubricants Division, Energy and Water Resources Laboratory, U.S. Army Mobility Equipment Research and Development Command--1976 →). The prime FRF candidates have comprised diesel fuel with either 10 percent water and 6 percent emulsifier (FRF-A), or 5 percent water, 3 percent emulsifier, and 0.2 percent antimist agent (FRF-B), respectively.

(molecular weight greater than 10^6) inhibit mist formation and thereby decrease the possibility of post-crash aircraft fires.⁽⁵⁾ In 1973, the Army's need for fire-resistant combat fuels for ground equipment necessitated a shift in research emphasis from rotary wing aircraft fuels to diesel fuels. Experimental studies⁽⁶⁻⁸⁾ had established that, in the bulk liquid state, hydrocarbon fuels could be rendered nonflammable by the use of halogenated fire suppressants dissolved in the fuel. As a result, the fifth generation fire-resistant fuel in the Army's modified fuel development program consisted of DF-2 diesel fuel containing 5% (liq vol) bromochloromethane.

Each of the first five generations of fire-resistant fuels proved effective for reducing fuel flammability hazards for either aircraft or ground equipment, or both. However, each displayed some undesirable features^(1-5,9,10) which represented unsatisfactory trade-offs for the intended application. Hence, none of these single approaches was selected by the Army for intensified applied research and development which could lead to ultimate field use.

B. Current Modified Fuel Research

The mechanisms by which flame inhibitors mitigate liquid hydrocarbon flammability hazards have not been fully identified.⁽¹¹⁾ However, results of the flammability and engine experiments conducted by the authors with diesel fuel containing 5 liq vol% bromochloromethane⁽¹¹⁾ suggested the dominance of physical mechanisms in rendering the bulk liquid fuel nonflammable.⁽¹¹⁾ Accordingly, substitution of water for the halon was investigated as an alternate and more innocuous means of achieving heat-absorption and inert-vapor-blanket effects. Also, the effect of including small quantities of an antimist agent in the water-containing fuel was investigated and found to be beneficial. The early candidate fire-resistant fuel was a macroemulsion, with water droplet sizes predominantly in the 1- to 20-micrometer range.⁽¹²⁾ These fuels were prepared by ultrasonic homogenization of water in the surfactant-containing diesel fuel. Feasibility studies conducted with such multiphase fuels, utilizing an unmodified LDT-465-T multifuel diesel engine, indicated no significant changes in engine power output for equal base fuel flow rates. Follow-through studies demonstrated that ultrasonically stabilized DF-2 diesel fuel containing 10 percent water and 2 percent surfactant dis-

played self-extinguishing ground fires (well above the base fuel flash point) when subjected to 20-mm High-Explosive Incendiary Tracer (HEIT) ballistic impact. Moreover, flow studies, corrosion tests, and a 420-hour endurance test in the LDT-465-T engine confirmed that no serious mechanical or operational problems should be anticipated for fuel temperatures above 0°C.⁽¹³⁾ These investigations did pinpoint potential minor problem areas and revealed that incorporation of a polymeric antimist agent in the water-containing fuel could improve the fuel fire resistance while decreasing the amount of dispersed water required in the formulation.

Major drawbacks of these particular emulsions were:

- Ambient temperature phase stability was relatively poor (\approx 1 month at 25°C).
- Thermally-induced depositing tendencies of the surfactant, according to the Jet Fuel Thermal Oxidation Tester (JFTOT) (ASTM D 3241) procedure, were high. A slight downward drift in power output during the aforementioned engine endurance test (\sim 4 percent per 100 hours) may have been caused by such deposition.
- Unique problems stemming from properties of antimist agents included:
 - Premature depolymerization of antimist agent because of shear effects during handling,
 - High filter back pressure, and
 - Fuel-blending difficulties.

The foregoing information on the Army's present-generation fire-resistant fuel was of a preliminary nature; however, all of the experimental findings consistently pointed to the feasibility of developing a practical fuel for ground vehicles which would reduce the fire vulnerability of combat equipment. Toward this end, the Army intensified its modified fuel research and development program with the objective of fielding a fire-resistant combat fuel.

Low-internal-phase-ratio water-in-oil emulsions, with and without an antimist agent, became the sixth, and current, generation in the Army's modified fuel program.

It is the purpose of this report to describe the ensuing experimental development of candidate FRF formulations which display diminished mist flammability and self-extinguishing pool fires, even at temperatures above the base fuel flash point.

III. PROGRAM OBJECTIVES

Extensive applied research plans were devised by the U.S. Army Mobility Equipment Research and Development Command/U.S. Army Fuels and Lubricants Research Laboratory (USAFRLRL) for developing fire-resistant diesel fuel. These included the major areas illustrated in Figure 1.

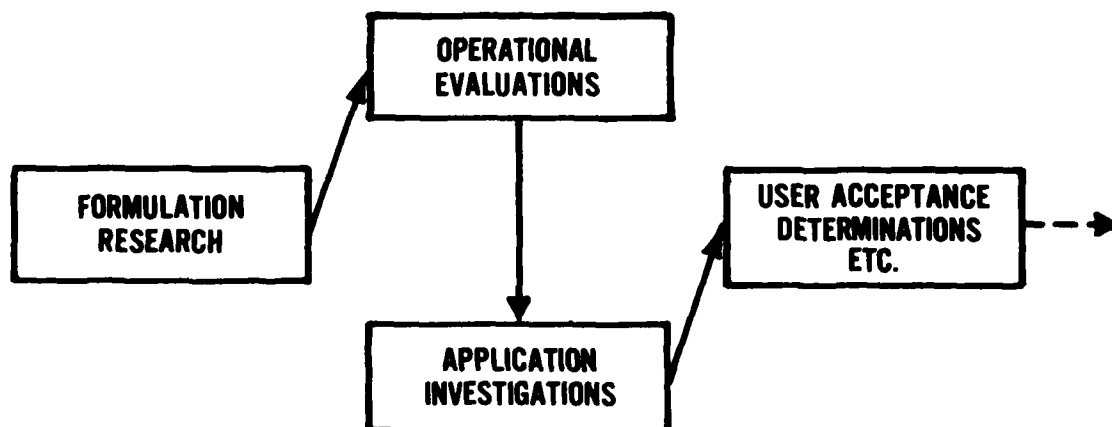


FIGURE 1. FLOW CHART OF INITIAL PHASES OF MERADCOM FRF DEVELOPMENT PROGRAM

Figure 2 indicates the detailed aspects of the planned "formulation research" phase of Figure 1. Figure 3 specifies the "operational evaluations" phase, and Figure 4 identifies the areas for "applications investigations."

Although these detailed plans shown in Figures 1 through 4 indicate activities by MERADCOM, AFLRL, U.S. Army Ballistics Research Laboratory/AFLRL, and NATICK, only those involving AFLRL are described or discussed in this report.

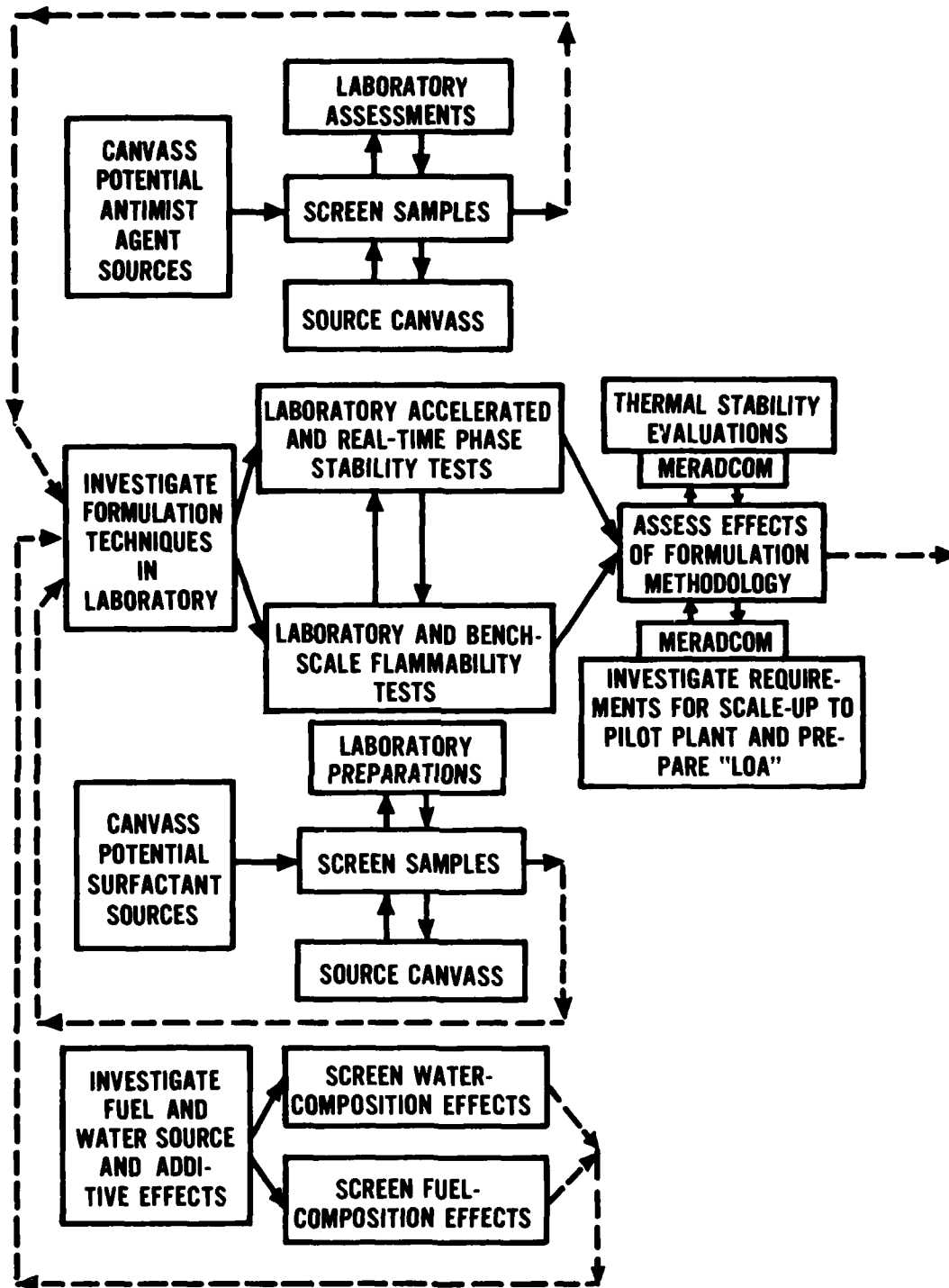


FIGURE 2. FLOW CHART OF "FORMULATION RESEARCH" PHASE OF FRF DEVELOPMENT PROGRAM

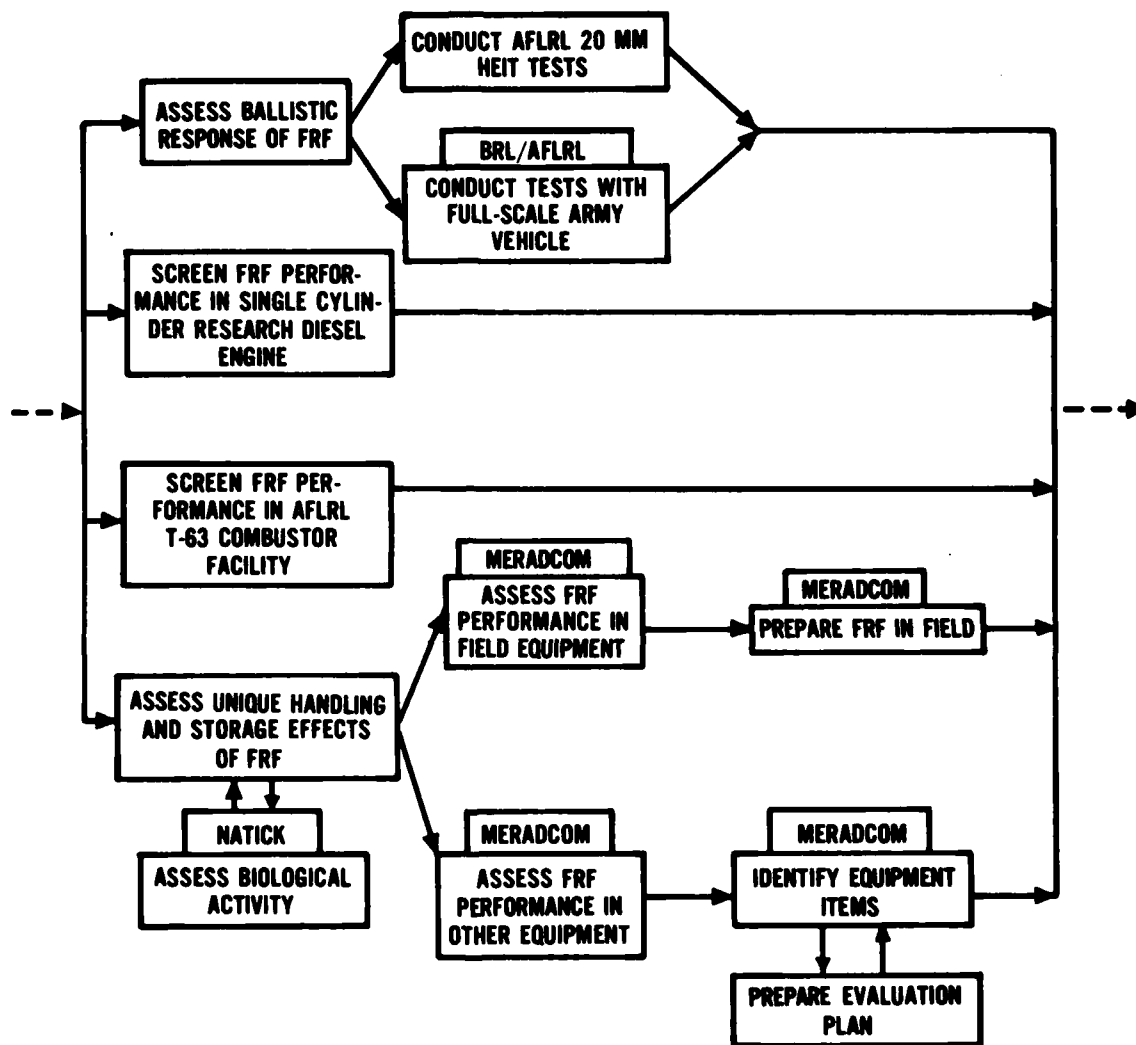


FIGURE 3. FLOW CHART OF "OPERATIONAL EVALUATIONS"
PHASE OF FRF DEVELOPMENT PROGRAM

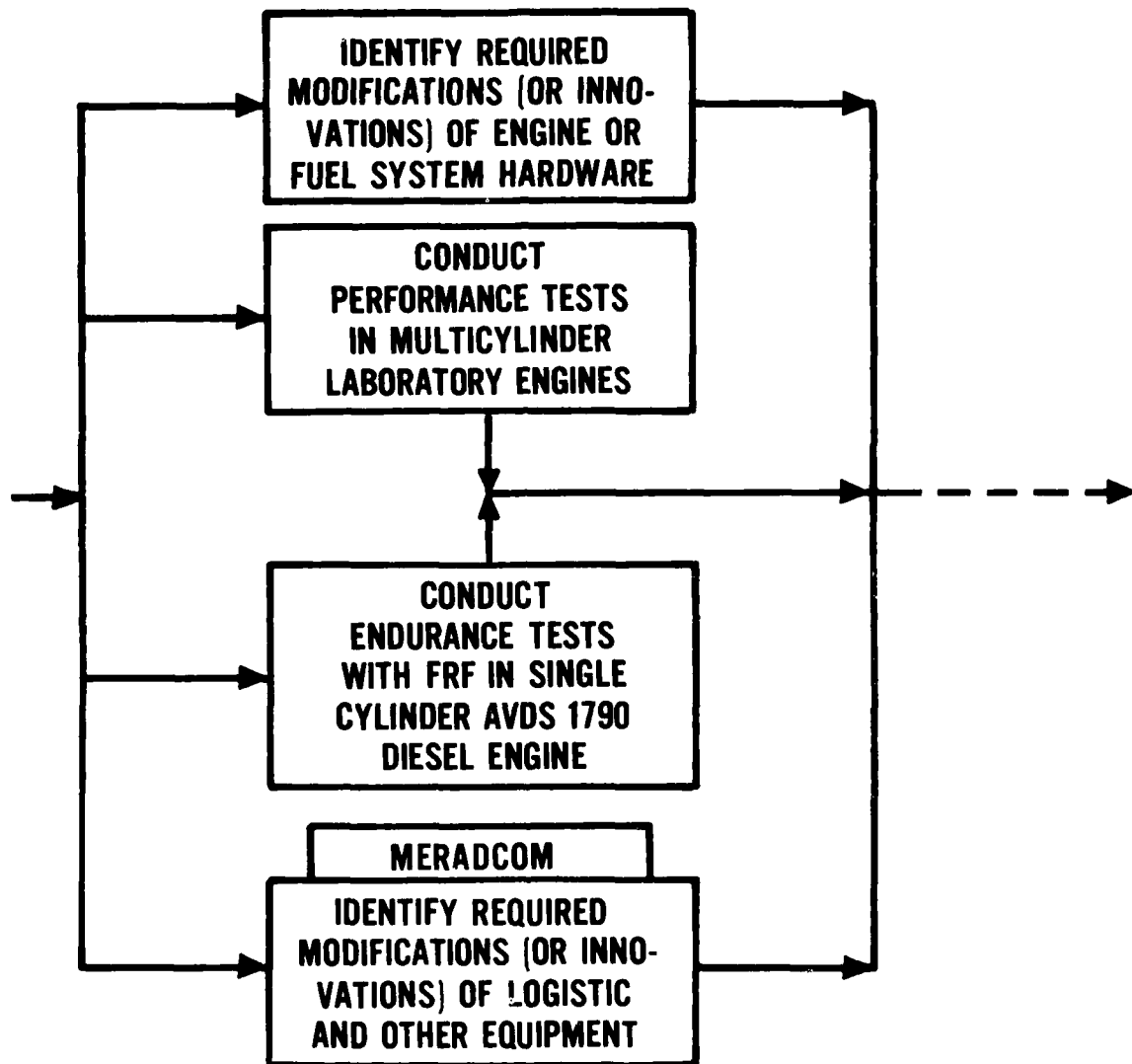


FIGURE 4. FLOW CHART OF "APPLICATION INVESTIGATIONS"
PHASE OF FRF DEVELOPMENT PROGRAM

IV. EXPERIMENTAL APPROACH

A. Investigation of Available Fire-Resistant Fuel Ingredients

1. Screening of Potential Surfactant Candidates

An extensive telephone canvass of potential suppliers of surfactants was conducted. The nature of the intended application was described, and the suppliers were requested to provide candidate samples representing their "best judgments." A list of suppliers providing samples is presented in Table 2. Screening tests were conducted on these samples using 10 percent de-ionized water and ultrasonic homogenization. In these screening tests, the efficiency of each surfactant was evaluated at the 2 vol% concentration level which corresponds with that of the previously investigated fire-resistant fuel emulsions made with mixed sorbitan/amide surfactants.

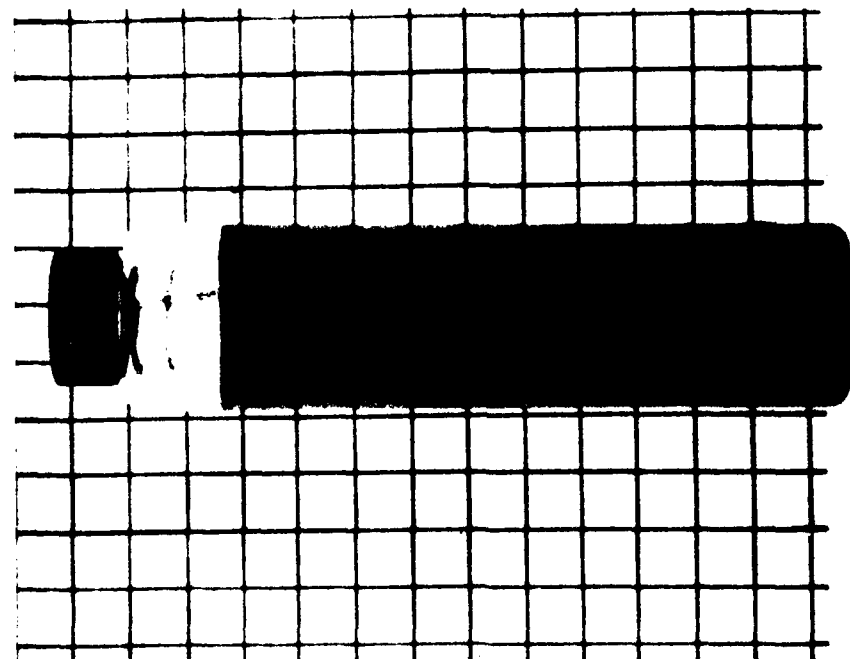
Candidate FRF formulations based upon the latter surfactants were subjected to intensive evaluations to characterize their physical, chemical, phase-stability, and flammability properties. These evaluations are described in subsequent sections of this report.

Among the surfactants subjected to screening, compositions were identified which produced clear to hazy emulsions with 10 percent water in diesel fuel. The most important feature of these latter blends is that the translucent emulsions are formed upon simple mixing of water with base fuel containing the surfactant. This appearance and behavior are consistent with published descriptions of microemulsions in which "...a mixed film adsorbs to the interface between the oil and water phases, creating a transient, negative free energy and causing the adsorbed monolayer to spontaneously achieve zero interfacial tension. This ensures that the system will remain dispersed and will not, as macroemulsions do, achieve equilibrium by separating into the original, mutually insoluble liquid phases."⁽¹⁴⁾ The cited reference also states that the diameters of the droplets in the microemulsions are less than one-fourth the average wavelength of white light, which is about 1400 Å. Hence, light can pass through such systems, so they appear translucent as illustrated for 10 vol% water and 6 vol% surfactant in Figure 5.

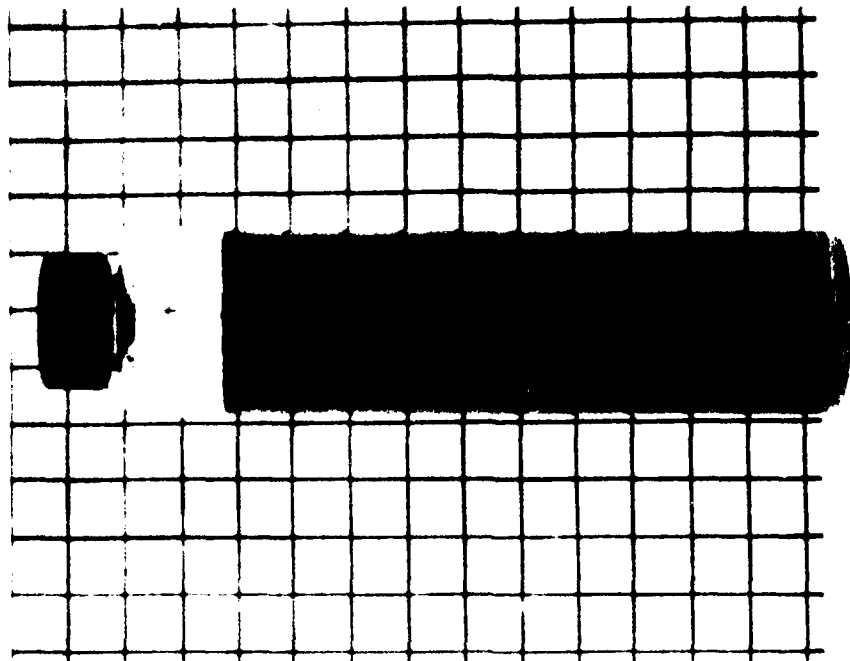
TABLE 2. LIST OF SURFACTANT SUPPLIERS PROVIDING SAMPLES
FOR FIRE-RESISTANT FUEL SURFACTANT SCREENING

- | | |
|---|---|
| 1. AMERCHOL
Talamadge Road
Amerchol Park
Edison, NJ 08817 | 10. Lonza, Inc.
22-10 Rt. 208
Fairlawn, NJ 07410 |
| 2. American Cyanamid Co.
Berdan Ave.
Wayne, NJ 07470 | 11. Mona Industries, Inc.
65 E 23rd Street
Paterson, NJ 07524 |
| 3. BASF Wyandotte Corp.
Industrial Chemicals Group
Wyandotte, Michigan 48192 | 12. PVO International Inc.
416 Division Street
Boonton, NJ 07005 |
| 4. CIBA-GEIGY Corp.
Dyestuffs & Chemicals Div.
Greensboro, NC 27409 | 13. The Richardson Co.
Organic Chemical Div.
2871 Lake Street
Melrose Park, IL 60160 |
| 5. Clintwood Chemical Co.
4342 S. Wolcotte Ave.
Chicago, IL 60609 | 14. Rohm and Haas, Co.
Independence Mall West
Philadelphia, PA 19105 |
| 6. Diamond Shamrock Corp.
Process Chemicals Div.
350 Mt. Kemble Ave
Morristown, NJ 07960 | 15. Scher Chemicals, Inc.
Industrial West
Clifton, NJ 07012 |
| 7. GAF Corp.
Chemical Division
140 W. 51st Street
New York, NY 10020 | 16. Stepan Chemical Co.
Northfield, IL 60093 |
| 8. IMC Chemical Group, Inc.
NP Division
4415 Harrison St.
Hillside, IL 60162 | 17. Troy Chemical Corp.
One Ave L
Neward, NJ 07105 |
| 9. Jefferson Chemical Co., Inc.
P.O. Box 53300
Houston, TX 77052 | 18. Union Carbide Corp.
Chemicals & Plastics
270 Paru Ave
New York, NY 10017 |
| | 19. Witco Chemical Corp.
Organics Div.
277 Park Ave
New York, NY 10017 |
-

The surfactant which produces these microemulsions with diesel fuel is known to be available from at least two different suppliers. It comprises the reaction products of two moles of diethanolamine and one mole of oleic acid.



Base Fuel
Referee-Grade Diesel Fuel
MIL-F-46162A(MR), Grade II



10% Water in Surfactant-
Stabilized Referee-Grade
Diesel Fuel

FIGURE 5. COMPARISON OF FIRE-RESISTANT FUEL WITH NEAT BASE FUEL

These include N,N-bis(2-hydroxyethyl)-oleamide, diethanolamineoleate soap, and excess diethanolamine. As discussed in subsequent portions of this report, modification of this composition is beneficial in the case of certain base fuels, the use of hard water (approximately 300 ppm total dissolved solids), or the addition of antimist agent. The modification of the commercial surfactant consisted of enhancing its hydrophilic character by increasing the soap content (see Table 3). This step was accomplished by reacting part of

TABLE 3. COMPARISON OF SELECTED PROPERTIES OF SORBITAN-TYPE AND AMIDE-TYPE SURFACTANTS

	Total Acid No., <u>mg KOH/g</u>	Ash, <u>wt%</u>	Existent Gum, <u>mg/100 ml</u>
Previously used surfactant mixture: [sorbitan fatty acid esters and substituted sorbitan fatty acid esters]	0.16	0.003	1337
Current unmodified surfactant mixture: [diethanolamine, N,N-bis(2-hydroxyethyl)- oleamide, and diethano- lamineoleate soap]	0.35	0.001	145*

* All of surfactant does not evaporate at 232°C test temperature.

the commercial product's excess diethanolamine with an additional amount of oleic acid at 50°-55°C for 10 to 15 minutes. According to one supplier, stabilization of the original or modified composition is achieved by heating the mixture at about 60°C for two days.

2. Screening of Potential Antimist Agent Candidates

An extensive telephone canvass of potential suppliers of antimist agents was conducted. The nature of the intended application was described, and the suppliers were requested to provide candidate samples if the suppliers believed the samples met the program requirements. The suppliers were informed that MERADCOM would follow with a formal letter explaining the Army position, indicating potential quantities of fuel involved, and requesting an expression of interest. Earlier studies have defined several criteria that must

be met in order for a substance to qualify as a viable antimist candidate. These criteria include shear stability, chemical stability, solubility in fuel and, of course, performance as an antimist agent. Samples of new candidate high-molecular-weight polymer materials were received as a result of this canvass and the MERADCOM letter. A list of suppliers providing samples is presented in Table 4.

TABLE 4. LIST OF SUPPLIERS PROVIDING SAMPLES FOR
FIRE-RESISTANT FUEL ANTIMIST AGENT SCREENING

- | | |
|---|--|
| 1. B.F. Goodrich Chemical Co.
6100 Oak Tree Blvd
Cleveland, OH 44131 | 5. The Firestone Tire & Rubber Co.
Central Research Laboratory
Akron, OH 44317 |
| 2. Continental Oil Co.
Chemicals Research
P.O. Box 1267
Ponca City, OK 74601 | 6. Goodyear Tire & Rubber Co.
Chemical Division
P.O. Box 5387
Houston, TX 77012 |
| 3. Dow Chemical U.S.A.
Central Research
Midland, MI 48640 | 7. Shell Chemical Co.
One Shell Plaza
P.O. Box 2463
Houston, TX 77001 |
| 4. Exxon Chemical Co.
P.O. Box 3272
Houston, TX 77001 | |
-

These candidate antimist agents were investigated with the objective of obtaining one or more antimist agents that could be used interchangeably with the agent AM-1.* A new antimist agent would be expected to be at least as shear stable and have rheological properties equivalent to those of AM-1. The following procedure was used to screen these candidates:

- Solubility characteristics were observed while placing the polymers in solution.
- If the solubility appeared to be acceptable, the antimist characteristics were evaluated with the mist flashback procedure.

* The AM-1 designation was assigned by AFLRL to a commercial fluid friction drag reducer to denote the first antimist agent studied by the Army. This agent comprises a long-chain hydrocarbon polymer having an average molecular weight in excess of 5×10^6 .

AM-1 is obtained from the manufacturer as a 5 wt% concentrate in a highly refined commercial solvent, "LPA," and it is diluted to 0.2 wt% concentration in the fuel by simple mixing. All other antimist agents were supplied to this laboratory as solid polymers. Each of the polymers except AM-1 was dissolved at 0.5% concentration in the referee-grade diesel fuel, AFLRL Code No. 7725. Dissolving of the polymer was usually accomplished in a 2-liter glass jar, equipped with mixing baffles, which was rotated at a tip velocity of 1.5 cm/sec while heating with infrared lamps to a fuel temperature of 57°C. After the stock solution had been obtained, further dilutions were made with the base fuel to arrive at a desired polymer concentration.

For purposes of comparison, polymer AM-15, was also dissolved at the same concentration in the fuel in a round-bottom three-neck flask that was immersed in an oil bath at 57°-60°C temperature. No appreciable difference was noted because of the different modes of dissolution. The effect on AM-1 of the above-described dissolution by rolling was investigated, and it was observed that the rotation mildly degrades the polymer. However, even after 26 days of rotation, AM-1 still exhibits excellent antimist properties.

Antimist agent FM-9 was also included in the screening program. This material was provided by the UK Royal Aircraft Establishment via the U.S. Federal Aviation Administration. A fuel blend was prepared in the reference grade diesel fuel that comprised 0.3 wt% FM-9 antimist additive. This fuel blend is known to exhibit fire-resistant properties. It was envisioned that if this fuel could be incorporated into an aqueous microemulsion, enhanced fire safety would result as in the case of AM-1-containing microemulsions. An attempt was made to disperse 5 vol% deionized (or tap) water in the FM-9-containing fuel using modified or unmodified surfactant. In each case, phase and polymer separation took place, indicating that FM-9 and those combinations of surfactants are incompatible with water.

Those candidate antimist agents which were soluble in the base fuel under the above-described conditions are listed in Table 5. They were evaluated with the AFLRL mist flashback procedure, and the results are described in subsequent sections of this report.

TABLE 5. LIST OF ANTIMIST AGENTS SCREENED FOR USE IN FRF-B
(Not Including FAA and RAE Candidates)

AFLRL Antimist Agent Code	Date First Batch Received	Date Last Batch Received	Description
AM-1	Dec 1971	Jan 1979	Fluid friction reducer
AM-3	May 1972	May 1972	Polyisobutene polymer
AM-11	June 1974	Feb 1978	Fluid friction reducer
AM-12	Nov 1977	Nov 1977	Polymer
AM-13	Nov 1977	Nov 1977	Polymer
AM-14	Nov 1977	Nov 1977	Polymer
AM-15	Nov 1977	Nov 1977	Polymer
AM-16	Jan 1978	Jan 1978	Polymer

As mentioned previously, among all of the screened antimist agents, only AM-1 is manufactured and marketed as a solution. None of the examined antimist agents displayed properties superior to those of AM-1 which could have justified the selection of such a solid agent requiring specialized dissolution procedures as a candidate FRF ingredient. Hence, AM-1 remains the sole antimist agent candidate in this FRF development program.

3. Procurement of Referee-Grade Base Fuel

A 37,850-liter (10,000-gal.) batch of referee-grade diesel base fuel (AFLRL Code No. 7225) was purchased for use in the FRF research program. This fuel was ordered under Military Specification MIL-F-46162A(MR), Grade II, and has been used exclusively in this program during the past year except for the first three months. During these three months, Ref. No. 2* diesel fuel (AFLRL Code No. 7124) was used pending receipt of the referee-grade fuel. In the previous year, a single batch of fuel (AFLRL Code No. 6938) had been used for all flammability and ballistic vulnerability evaluations. According to flammability tests, this older batch is less flammable than the present referee-grade fuel. In an effort to explain differences in flammability between FRF base fuels, precision gas chromatography and boiling point distribution determinations were performed on the referee-grade fuel and the

* Federal Test Standard 791B, Method 341.4.

previously used base fuel. The results of these determinations showed essentially superimposable curves in the range of 0 to 1 percent distilled. However, differences increased as the distillation continued. These results indicated a lower overall distillation temperature for the referee-grade fuel when compared to the other base fuel. Laboratory distillation data (ASTM D 86) demonstrate that the average boiling point of the referee grade fuel (7225) is about 28°C lower than that of the previous fuel batch (6938) (Table 6 and Figure 6). In fact, as illustrated in Figure 6, the distillation curve

TABLE 6. COMPARISON OF PROPERTIES OF MIL-F-46162A(MR), GRADE II REFEREE-GRADE DIESEL FUEL WITH PREVIOUSLY USED BALLISTIC TEST DIESEL FUEL

	Previously Used Ballistic Test Fuel	MIL-F-46162A(MR), Grade II Referee-Grade Fuel
AFLRL Fuel Code	6938	7225
Density, g/ml at 15.6°C	0.86	0.84
Flash Point, °C	68	60
Fire Point, °C	107	91
Pour Point, °C	-20	-24
Kin. Viscosity, cSt at 40°C	3.3	2.2
Aromatics by FIA, vol%	34.5	27.5
Surface Tension, dyne/cm	29	28
Distillation (ASTM D 86)		
Temp, °C		
IBP	171	166
10%	238	219
20%	260	229
30%	269	234
40%	274	239
50%	281	244
60%	289	241
70%	299	258
80%	311	272
90%	330	296
FBP	363	358

of this base fuel approximates the upper limit for DF-1 arctic diesel fuel whereas that of the earlier ballistic test base fuel corresponds approximately to the upper limit for DF-2 diesel fuel. As shown in Table 6, most other physical properties of these base fuels conform to the differences indicated by the distillation data. The Ref. No. 2 base fuel was not employed in flammability studies, hence, it is not included in the comparisons of Figure 6 or

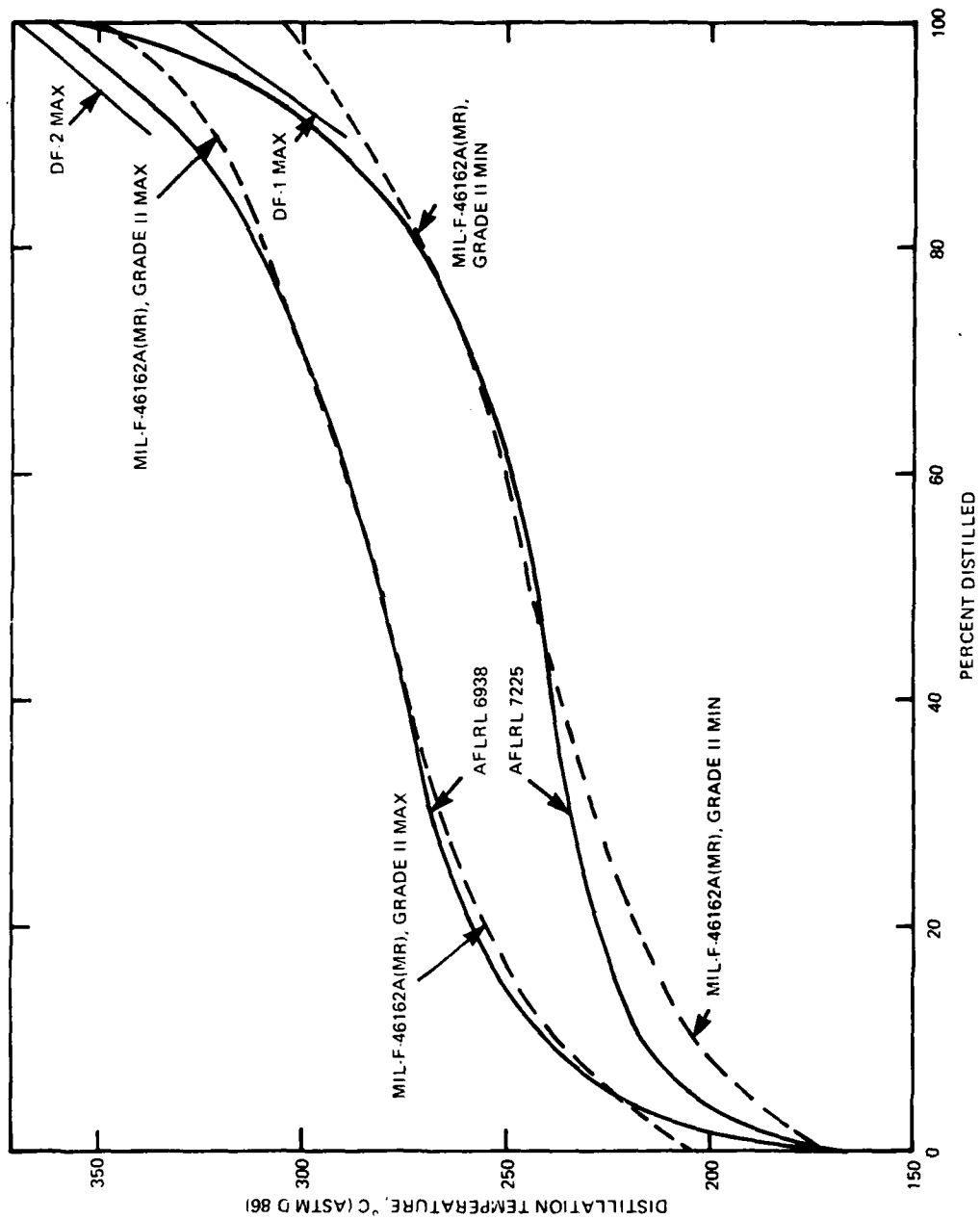


FIGURE 6. COMPARISON OF FUEL DISTILLATION DATA WITH SPECIFICATION DATA

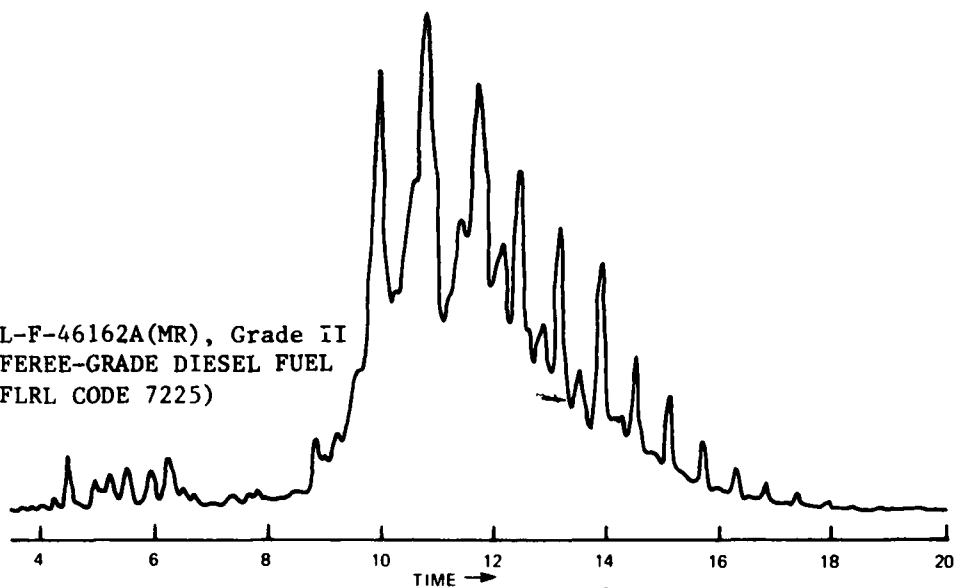
Table 6. The above-noted differences in volatility between referee fuel, code 7225, and fuel, code 6948, are graphically apparent when component-distribution gas chromatograms are compared in Figure 7. The upper chromatogram is shifted to the left relative to the lower one, indicating higher volatility. Fortunately, the present base fuel represents a "worst case" from the flammability viewpoint which is appropriate for its use in developing a fire-resistant fuel.

The as-delivered referee-grade fuel, even though containing antioxidant, did not meet the accelerated stability (ASTM D 2274) specifications. Additional antioxidant was added which produced an acceptable rating. Specification properties of the referee fuel are compared with MIL-F-46162A(MR), Grade II requirements in Table 7.

TABLE 7. MIL-F-46162A(MR) REFEREE-GRADE DIESEL FUEL PROPERTIES

Property	Grade II Specification Value	Actual Value
Gravity @ 15.6°C °API	33-37	36.1
Density @ 15.6°C, g/ml	0.84-0.86	0.844
Flash Point, °C	> 56	60
Fire Point, °C	---	91
Cloud Point, °C	< -13	-21
Pour Point, °C	< -18	-24
Kin. Viscosity (37.8°C), cSt	2.2-3.2	2.17 at 40°C
Surface Tension, dyne/cm	---	28
ASTM Distillation (D 86), °C		
Initial Boiling Point	171-204	166
10% Distilled	204-238	219
50% Distilled	243-282	244
90% Distilled	288-321	296
End Point	304-349	358
Carbon Residue on		
10% bottoms, wt%	< 0.20	0.15
Sulfur, wt%	0.35-0.70	0.35
Cu Strip Corrosion, 3 hr @ 50°C	Report	1A
Ash, wt%	< 0.02	0.01
Accelerated Stability, mg/100ml	1.0	0.6
Neut. No., mg/100ml	< 0.01	0.01
Aromatics, vol% (FIA)	> 27	27.5
Heat of Combustion, Gross, J/kg	Report	42.3 x 10 ⁶
Cetane No.	> 42	48
Existent gum, mg/100ml	---	3.9

MIL-F-46162A(MR), Grade II
REFEREE-GRADE DIESEL FUEL
(AFLRL CODE 7225)



PREVIOUSLY-USED
BALLISTIC TEST
DIESEL FUEL
(AFLRL CODE 6938)

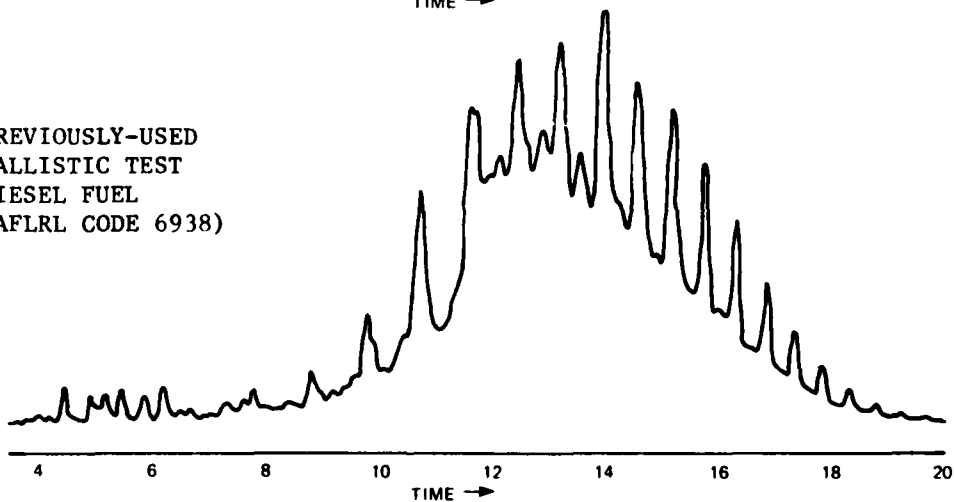


FIGURE 7. COMPARISON OF GC COMPONENT DISTRIBUTIONS FOR REFEREE-GRADE AND PREVIOUSLY USED BALLISTIC TEST FUEL

B. Evaluations of Physical and Chemical Properties

Because of observed complex interactions resulting from variations in the compositions of base fuel, surfactant, and water, an extensive series of laboratory evaluations of physical and chemical properties has been an essential element of the fire-resistant fuel development program. Complete military specification tests have been conducted on base fuels and fire-resistant fuel blends made from them. Laboratory evaluations have also included determinations of thermal stability, surface tension, electrical conductivity, low-temperature viscosity, foaming, corrosion, and elastomer compatibility. In addition, infrared and ultraviolet absorption spectra of selected base fuels and blending stocks have been measured in order to characterize the hydrocarbon type composition of the fluids. Results of these laboratory experiments are presented in subsequent sections of this report.

C. Phase Stability Tests

The emulsifier concentration of 2 vol% used during the initial screening program was too low to produce stable emulsions with a wide variety of diesel (DF-2) base fuels. Also, microemulsions containing only 2 percent surfactant were not stable when subjected to cycling temperatures. Consequently, extensive experimental phase stability studies were conducted to select more realistic compositions both with and without 0.2 wt% AM-1 antimist agent. These experiments were made using several different base fuel compositions, water contents, water electrolyte concentrations, surfactant contents, and surfactant compositions.

Most of the phase stability studies were conducted at ambient temperatures (approximately 22°C). However, the more promising formulations were also evaluated for six cycles between the limits 2° and 55°C. In addition, a limited investigation is being conducted to evaluate the effects on phase stability of storage in metal containers under various conditions which include: 4°, 24°, 43°C, and outdoors with and without weather protection. Results of the various phase stability investigations are presented in subsequent sections of this report.

D. Diesel Engine and Gas Turbine Combustor Tests

1. Diesel Engine Performance Evaluations

Initial evaluations of FRF performance were made in a 43-CID, single-cylinder CLR research engine. Injection timing, rates, and spray nozzles were the same as those previously optimized for 100 percent diesel fuels.

The performance of the FRF emulsions was evaluated in four multicylinder military engines. The engines were unmodified, and thus reflect the behavior of vehicles if the FRF is simply introduced into the field without any vehicle changes.

The engines used for these short-term performance evaluations include the DD3-53 and the DD6V-53T, which are members of a family of open-chamber, direct-injection, two-cycle diesel engines widely used in military tactical and combat vehicles.

These water-cooled, two-cycle engines have their intake ports in the cylinder liner and use four exhaust valves per cylinder. Both of the engines have a Roots-type gear-driven blower to increase the intake air flow for better cylinder scavenging. In addition, the 6V-53T engine is fitted with a turbo-charger to further increase the airflow.

The fuel system for both engines normally consists of a sock-type filter, a fuel transfer pump, then a secondary pleated-paper filter. This system then uniformly distributes fuel to the unit injectors at each cylinder. These unit injectors contain a sintered metal filter at the fuel inlets. Excess fuel is then returned to the fuel tank through the injectors and cylinder head where it serves as a cooling fluid.

The AVDS-1790-2C engine is a twelve-cylinder, open-chamber, air-cooled engine used in the M60 tank. A single-cylinder assembly from this engine was used to evaluate the fire-resistant fuel. This laboratory engine comprised an AVDS-1790-2C cylinder, connecting rod, and injector assembly mounted on a Cooperative Universal Engine (CUE) crankcase and is illustrated

in Figure 8. This crankcase was originally developed for testing air-cooled aircraft engine cylinder assemblies and was subsequently employed in the development of the 12-cylinder AVDS-1790 engine which powers the M60 battle tank. The turbochargers normally on the engine were simulated by providing heated compressed air and throttling the exhaust gas flow to increase the pressure.

This simulation of the turbocharging system meant that any changes in exhaust gas energy due to fuel effects would not be reflected in the intake air supply, as might occur with an actual turbocharger.

The fuel supply system consists of a fuel transfer pump and pressure relief valve, a pleated paper filter, and a Bosch fuel injection pump. The fuel injection system consists of a Bosch injector with a 12-millimeter barrel and plunger.

The fourth engine used in these evaluations was from a family of multifuel, four-cycle, direct-injection engines designed by the Army around the MAN combustion chamber design. The LD-465 is a normally aspirated version of this engine. As expected from its description, the engine can operate with a wide variety of fuels ranging from gasoline to middle distillate fuels or crude oils.

2. CUE-1790 Diesel Engine Endurance Tests

In this program, three 250-hour endurance tests were conducted in the CUE-1790 engine using neat fuel and FRF-A made with deionized water and tap water. The endurance tests were conducted to evaluate the combustion chamber deposit formation tendencies of FRF-A and the effects on cylinder wear. Since the engine friction is considerably different in this single-cylinder assembly than in the full-scale engine, the CUE engine was operated at 1800 rpm at the full-scale engine peak torque speed, and with diesel fuel rate adjusted to one-twelfth of the full-scale engine's rated fuel rate. This produced an indicated mean effectiveness pressure (IMEP) that should be equal to that obtained with the full-scale engine. The endurance test was then conducted with the FRF-A at the same speed and IMEP settings. This

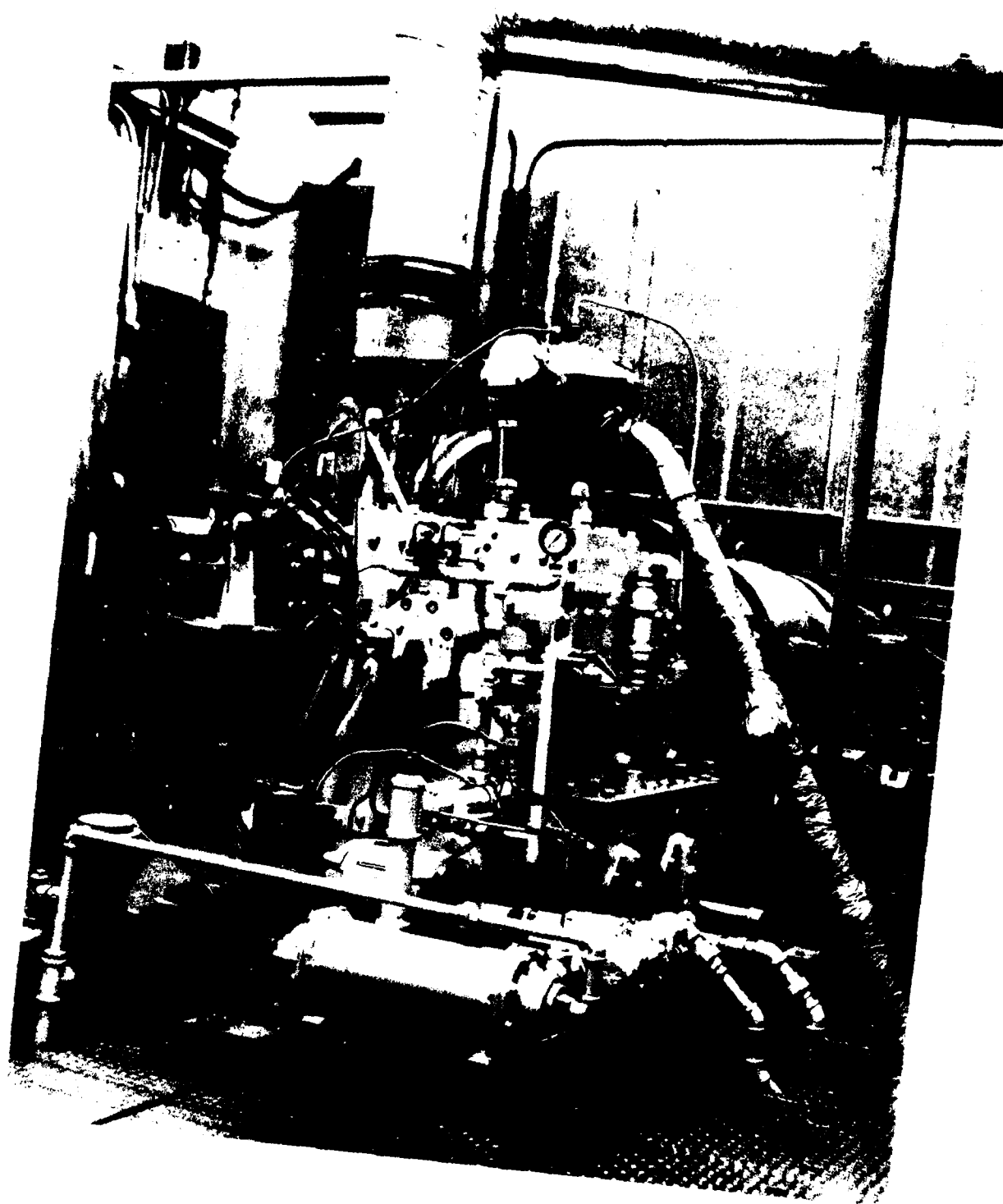


FIGURE 8. PHOTOGRAPH OF CUE 1790 SINGLE-CYLINDER
LABORATORY ENGINE FACILITY

procedure was an attempt to keep the same piston loadings that would be found in the AVDS-1790-2C engine with the fueling rate readjusted for the FRF.

3. Turbine Combustor Performance Evaluations

FRF gas turbine combustion tests were conducted in an Army-owned facility located at SwRI. This facility was designed specifically to study fuel-related influences on the operation of advanced Army turbine engines. Unvitiated air, at up to 1.1 kg/sec, is preconditioned at up to 16 atm and up to 1100K, with rehumidification if desired. Flow rates and test-condition data are reduced on-line, thereby yielding immediate test reports of flow rates, exhaust temperature profiles, emissions data, and combustion efficiency. Tests conducted in support of this FRF development program utilized an Allison T-63 combustor section (without moving parts). Results are described in a subsequent section of this report.

E. Evaluation of Flammability/Vulnerability Characteristics

Several different flammability evaluation procedures have been developed in support of the Army's fire-resistant fuel development program. These include mist-flashback, horizontal-flame-spread, and impact-dispersion tests which have served as the primary flammability-screening procedures for candidate antimist agents and surfactants. Also, standardized (e.g., ASTM-type) laboratory measurements of flash point, fire point, and autoignition temperature were conducted on promising formulations.

Additionally, ballistics tests were conducted using 20-mm high-explosive-incendiary-tracer projectiles (HEIT) and 3.2-inch, precision shaped charges. The foregoing procedures are described and discussed in subsequent paragraphs.

1. Mist Flashback Techniques

A mist flashback technique, developed in the Army Fuels and Lubricants Research Laboratory⁽¹⁵⁾, is highly effective in demonstrating differences

in the ease of atomization by air impingement among various fuels, especially those containing antimist agents. As illustrated in Figure 9, fuel is delivered

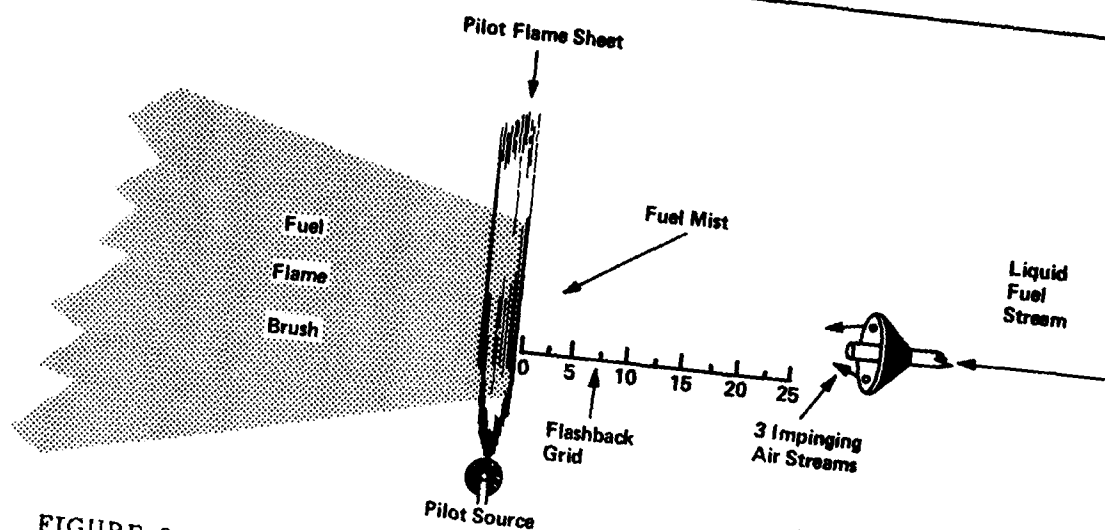


FIGURE 9. SCHEMATIC REPRESENTATION OF MIST FLASHBACK TEST

through a capillary at a controlled rate, and three impinging air streams form a mist at the point of impingement. The fuel mist passes through an overwhelming ignition source (flame sheet) to avoid marginal ignition problems. The flame propagation from the ignition source toward the fuel capillary is recorded utilizing a video camera and tape recorder. These results can then be carefully evaluated at some later time by measuring directly from a graduated scale located beyond the flame. A mist flashback rating, expressed as a mean distance of flashback, is assigned to the fuel. This average rating is based on triplicate experiments, each conducted at three different misting air rates (ranging from relatively low to extremely high shear conditions), *i.e.*, the average of nine values. This flashback concept provides a numerical measure of mist flammability, and it has proved to yield highly repeatable data.

2. Horizontal Flame Spread

Horizontal flame spread, or "pool burning" is evaluated in a controlled-temperature flame channel. This horizontal flame spread experiment utilizes

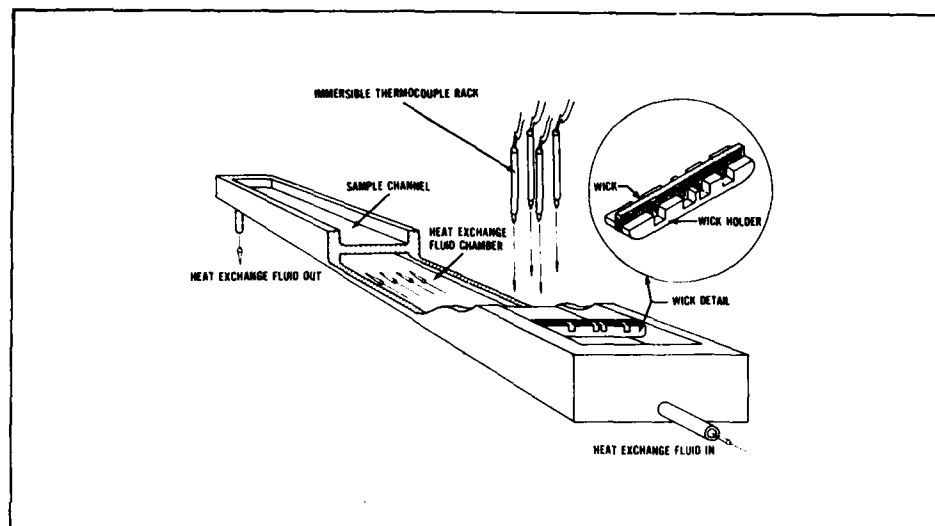


FIGURE 10. HORIZONTAL FLAME-SPREAD JACKETED CHANNEL

the jacketed device illustrated in Figure 10. In this test procedure, the channel is preheated to the test temperature and is then completely filled with test fluid which has been preheated to the same temperature. The ignition source is a partly submerged asbestos wick which is ignited remotely.

The elapsed time until the onset of flame propagation is measured and the rate of flame propagation along the channel is recorded on video tape for future data reduction.

3. Impact Dispersion Technique

Mist flammability and pool-burning effects are also evaluated by another technique which is referred to as the impact dispersion procedure. Impact dispersion experiments are conducted in a well ventilated, enclosed facility developed for this purpose (see Figure 11). These tests involve allowing a 2-liter glass vessel, containing about 1.5 liters of fuel, to fall freely 6 m onto

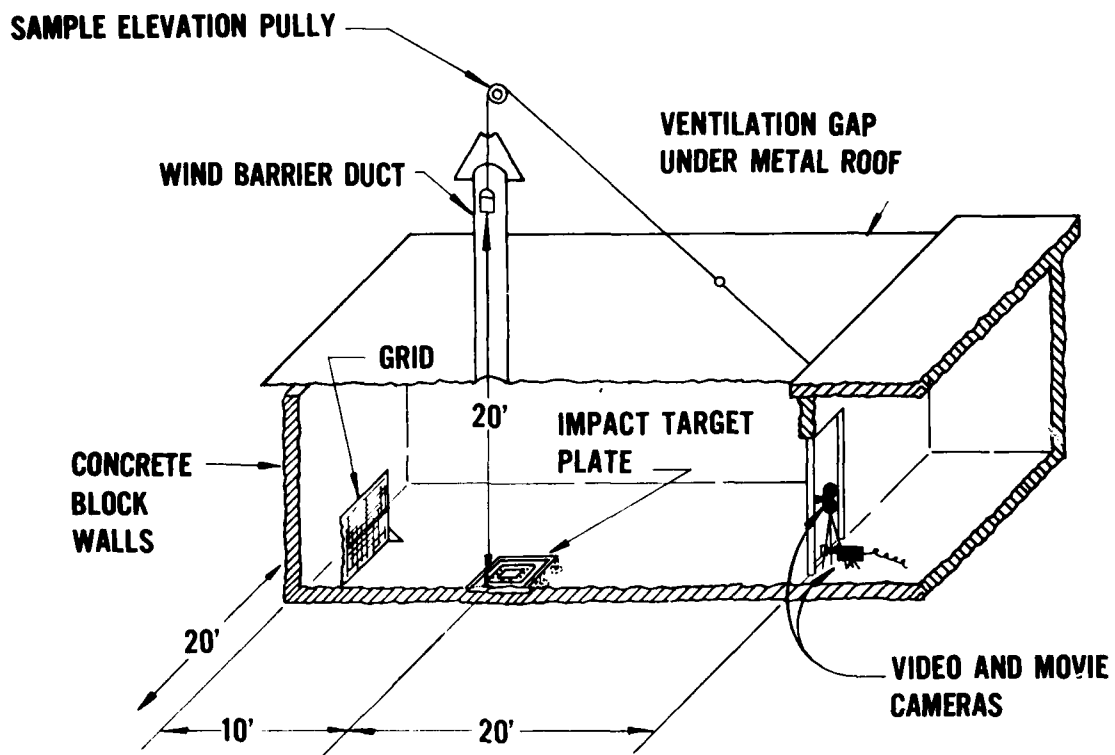


FIGURE 11. ILLUSTRATION OF IMPACT DISPERSION TEST FACILITY

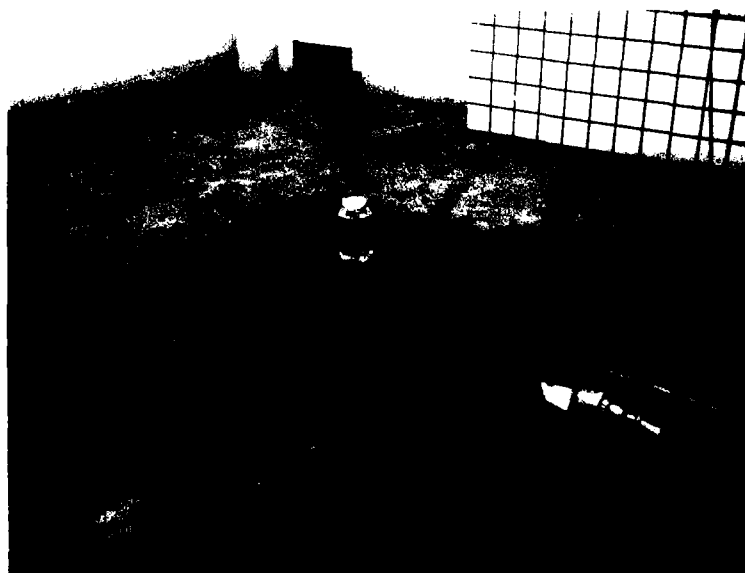


FIGURE 12. IMPACT PLATE AND PILOT ARRAY WITH SAMPLE AND SOLENOID RELEASE MECHANISM LOWERED FOR DISPLAY

a steel target plate with the point of impact being surrounded on two sides by gas pilot flames. The target plate comprises a horizontal (see Figure 12), elevated 2.5-cm thick steel plate with electric surface heaters attached to its underside so that its upper surface temperature can be adjusted and controlled.

The glass containers are filled to an ullage of about 2 percent of the total volume for each test. A television camera, located about 6 m from the impact point, is used to document test results on video tape. A background grid provides a dimensional frame of reference, and subsequent examination of the video tape by slow motion (and stop action), as illustrated in Figure 13, provides reduced data. Tests are conducted at several different temperatures, from about 25° to 99°C, by preheating the fuel sample and the steel target plate independently to the desired temperatures. This procedure has been shown to provide a quick, inexpensive, repeatable method for evaluating mist flammability and pool-burning characteristics of fluids.

4. Ballistic Tests

A relatively inexpensive ballistic test procedure was developed to provide means for evaluating the relative fire vulnerability of various fluids of interest for Army applications.⁽¹⁶⁾ The technique employs 20-mm high-explosive-incendiary-tracer projectiles fired into partly filled fluid containers. It yields repeatable results which establish both transient fireball effects and residual pool-burning tendencies. The ballistic range has three major components: a 20-mm Mann rifle assembly; a fuel tank target, including an actuator plate; and video and 16-mm movie film recording equipment. Figure 14 illustrates the overall experimental setup. The hemicylindrical target enclosure is constructed from corrugated steel culvert pipe, 0.3-cm thick, 4.6-m wide, 2.7-m high, and 3.3-m deep. The 20-mm Mann rifle assembly is located under an open shed with the rifle barrel being mounted in a universal cradle. All firings and high-speed 16-mm recordings are remotely triggered by a solenoid. A real-time 16-mm motion picture camera and video recorder are used also to record the events following impact.



FIGURE 13a. TRANSIENT FIREBALL EFFECTS OBSERVED IN IMPACT DISPERSION TEST OF FRF-A AT 77°C



FIGURE 13b. NEGLIGIBLE FLAMMABILITY OBSERVED WITH FRF-B IN IMPACT DISPERSION TEST AT 77°C

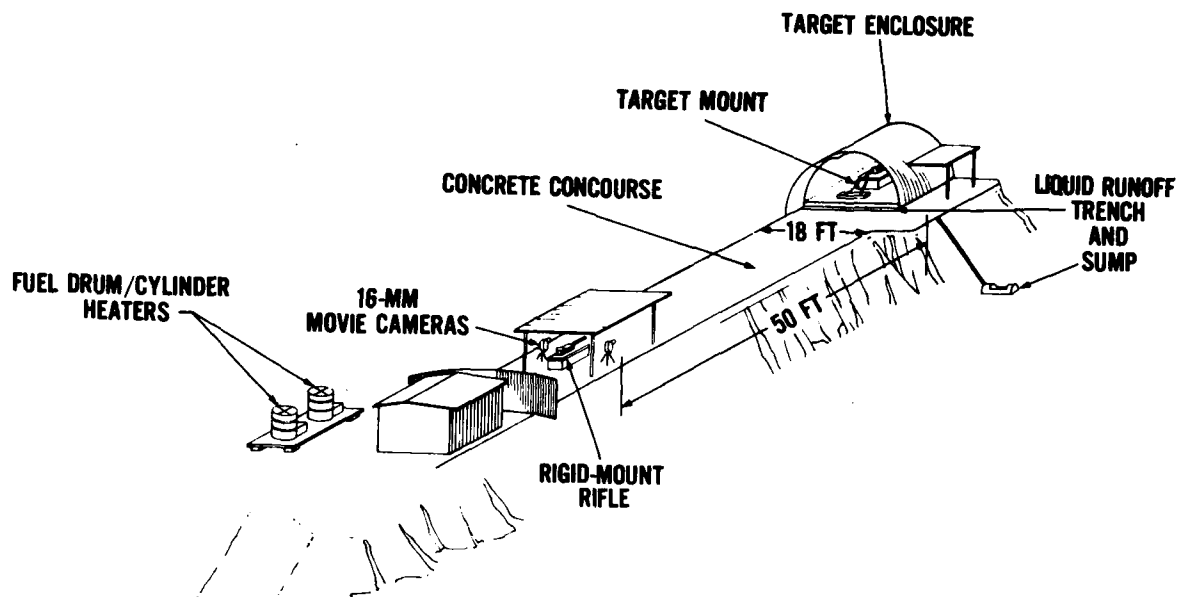


FIGURE 14. ILLUSTRATION OF BALLISTIC RANGE
USED FOR 20-MM HEIT EVALUATIONS

Figure 15 illustrates the fuel target assembly. The target is an expendable 114-liter steel drum meeting DOT-17E-203-73 specifications. This moderately

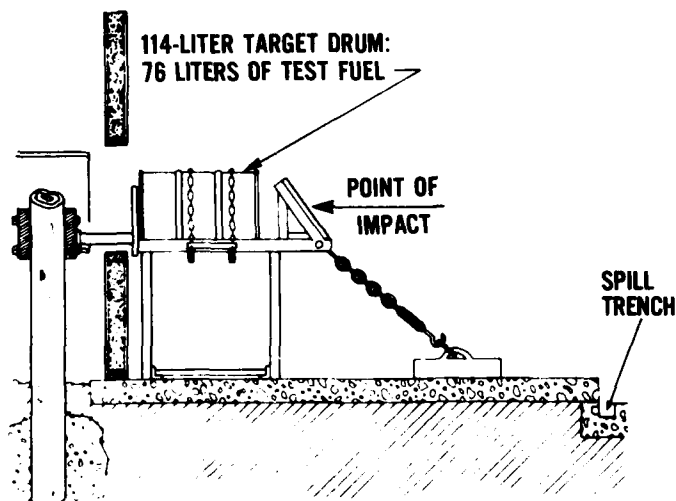


FIGURE 15. FUEL DRUM TARGET ASSEMBLY

priced target provides consistent responses to the ballistic impact. Projectile impact plates are placed 0.3 m in front of the face of the drum to serve as fuse actuator plates. These 0.3-m square plates are fabricated from 0.6-cm thick 6061-T6 aluminum.

A relatively high fluid test temperature (77°C) was selected for this test with the objective of providing a severe fire-hazard exposure. Military studies have reported bulk fuel-temperatures up to about 77°C in desert operations. On this basis, the test procedure appears to provide a realistic assessment of the ballistic vulnerability of candidate fire-resistant fuels. A typical fireball for a neat diesel fuel test is illustrated in Figure 16. The repeatability and reliability of the method have been shown to be satisfactory.



FIGURE 16. TRANSIENT FIREBALL EFFECTS OBSERVED WITH NEAT DIESEL FUEL IN AFLRL 20-MM HEIT BALLISTIC TEST

V. EXPERIMENTAL RESULTS

Experimental results obtained with all of the various combinations of base fuels, surfactants, antimist agents, and water qualities evaluated during this

investigation are not presented. Rather, those for the most promising fire-resistant diesel fuel candidates are described and discussed.

A. Candidate Formulations

In order to expedite the early use of a fire-resistant combat diesel fuel by the U.S. Army, only two promising candidate fuel formulations were selected for detailed experimental optimization. These candidates were chosen on the basis of favorable exploratory evaluations of phase stability, physical properties, flammability, and engine performance when formulated with referee-grade base fuel and the previously described unmodified surfactant. To simplify discussion of these candidates, they have been identified as FRF-A and FRF-B. FRF-A contains 10 vol% water and 6 vol% nonhydrocarbon surfactant with the remaining 84 vol% being base fuel. FRF-B contains 5 vol% water, 3 vol% nonhydrocarbon surfactant, and 0.2 wt% hydrocarbon antimist agent, with the remaining 92% being base fuel. Typical specification-type properties of these candidate formulations are compared with those of the referee-grade base fuel in Table 8. In addition to these data, experimental measurements indicate that FRF-A and FRF-B have essentially the same surface tension and electrical conductivity as the base fuel from which they are made; hence these properties do not appear of importance in the evaluation of the FRF formulations.

B. Phase Stability

Aside from the ability to mitigate fuel fire vulnerability, the single most important property of the candidate fire-resistant fuel formulations is that of phase stability. If the candidate FRF formulations remained as true microemulsions under all storage and handling conditions, they would display indefinite long-term phase stability. It has been observed in this laboratory that, in some cases, samples of such microemulsions have remained translucent for more than a year. However, in many cases, it has been observed that subtle batch-to-batch differences may result in bulk phase separation in apparent microemulsions several months after their initial blending. Higher surfactant-to-water ratios may alleviate this problem.

TABLE 8. REFEREE-GRADE-BASE-FUEL FIRE-RESISTANT FUEL SPECIFICATION-TYPE PROPERTIES

Property	Referee Grade Base Fuel MIL-F-46162A(MR), Grade II	FRF-A: Referee Fuel Plus 10 vol% Deionized Water Plus 6 vol% Surfactant		FRF-B: Referee Fuel Plus 5 vol% Deionized Water Plus 3 vol% Surfactant Plus 0.2 wt% Antimist	
			Surfactant		Agent
Gravity @ 15.6°C °API	36.1		36.1		34.0
Density @ 15.6°C, g/ml	0.844		0.857		0.853
Cloud Point, °C	-21		**		**
Pour Point, °C	-24		-23		-26
Kin. Viscosity, @ 40°C, cSt	2.17		3.52		7.04
Carbon residue on 10% bottoms, wt%	0.15		0.20		0.08
Sulfur, wt%	0.35		0.29		0.32
Cu strip corrosion, 3 hr @ 50°C	1A		1A		1A
Pipeline corrosion test (NACE TM-01-72)	A		A		A
Ash, wt%	0.01		0.00		0.00
Neut. No., mgKOH/100ml	0.01		0.74		0.84
Aromatics, vol% (FIA)	27.5		23		25
Heat of combustion, net, J/kg	42.3x10 ⁶		36.6x10 ⁵		39.7x10 ⁶
Cetane No.	48		41		46
Existent gum*, mg/100ml (wt%)	3.9(0.0)		1100(1.3)		424(0.5)

* All of surfactant does not evaporate at 232°C test temperature.

** The conventional cloud point cannot be determined because of the hazy nature of microemulsions.

In order to assure development of FRF formulations which will be stable for at least several months, investigations have been conducted to assess effects on phase stability of temperature, storage conditions, fuel composition, and water composition.

Either of two different surfactant compositions could be used for formulating FRF-A or FRF-B fuel blends. One of these was the previously described unmodified surfactant, and the other was modified by increasing, by 2.5 percent, the diethanolamine-oleic acid soap content in the manner described previously.

1. Temperature Effects on Phase Stability

Temperature cycling of the referee-grade base fuel, FRF-A and FRF-B, was conducted using modified surfactant. All three samples underwent six temperature cycles between 2° and 55°C for 7 hours at each temperature. The base fuel developed a trace of black precipitate due to its oxidative instability. Neither of the aqueous fuels deteriorated in this sense, but both showed traces of white "cream" at the bottom of their containers. This white substance, however, was easily redispersed in the formulation upon simple mixing.

The six-month storage stability evaluation (at 4°, 24°, 43°C, and outdoors with and without weather protection) has not yet been completed. The effects of repetitive freeze-thaw cycles have not been evaluated.

All of these temperature effects have been investigated only in a preliminary manner at this time, and plans include more detailed studies of such effects.

Temperature effects on thermal oxidation stability were briefly investigated using the ASTM D 3241 thermal oxidation stability test, and the results are presented in Appendix A.

2. Water Composition Effects on Phase Stability

Preliminary study of water purity effects on the phase stability of microemulsions indicated the well-known fact that salts (electrolytes) may destabilize emulsions. When a FRF-A microemulsion is prepared from the referee-grade diesel fuel and deionized water with unmodified surfactant, the product remains stable for at least several months. Substitution of tap water containing approximately 300 ppm total dissolved solids for deionized water results in an unstable macroemulsion. In FRF-B type compositions, microemulsions were produced from a number of commercially available diesel fuel with both deionized and tap water. This apparent stabilizing effect of AM-1, however, was not observed with the referee grade base fuel. Factors involved in water composition tolerance apparently include the exact chemical identities of the emulsifying agent ingredients as well as of the fuel constituents. The effect of pH values between 4 and 9 was found to be negligible.

3. Fuel Composition Effects on Phase Stability

In order to evaluate the effects of fuel composition on FRF phase stability, a ternary pure-component model system was investigated. The system's three components were n-hexadecane (cetane), methylnaphthalene, and decahydronaphthalene (decalin). Emulsions were made with deionized water, as-received or modified surfactant, and various concentrations of the three hydrocarbon compounds. Neither surfactant was effective in the presence of high, but typical, concentrations of the aromatic hydrocarbon. Accordingly, this pure component experimental approach was abandoned in favor of a more realistic approach.

Ten commercial fuels were obtained and analyzed, and their surfactant requirements were determined. Analytical data on these ten fuels and the two base fuels used in ballistic tests are summarized in Table 9. Also listed in this table are the surfactants required by these fuels to form microemulsions of FRF-A and FRF-B with deionized water and tap water containing about 300 ppm total dissolved solids (TDS).

TABLE 9. COMPOSITION OF VARIOUS DIESEL FUELS AND THEIR SURFACTANT REQUIREMENTS FOR STABLE MICROEMULSIONS

Base Fuel Description					
Refinery Sample	Referee-Grade	Refinery Station Sample	Service Station Sample	Service Station Sample	NATO P-54
6938	7225	7896	7907 7908	7909 7910	8652
Base Fuel Code No.					
Density, g/ml @ 15.5°C	0.860	0.848	0.847	0.850	0.835
Disillation:					
ASTM D 86, °C					
I BP	171	166	184	206	182
5%	219	201	209	227	209
10%	237	218	222	237	220
50%	281	244	266	276	266
90%	329	294	312	316	312
EP	363	358	336	332	333
Aromatics by HPLC, wt% HPLC, wt%	30.2	27.5	31.5	26.1	21.4
Aromatic Ring Carbon by UV, wt%					
Mononuclear	7.63	7.08	9.00	7.43	
Dinuclear	9.61	11.47	9.45	8.68	
Trinuclear	0.46	0.31	0.41	0.30	
Total	17.70	19.86	18.92	16.41	
Surfactant Required for Stable Microemulsion in: Deionized Water;					
FRF-A	u	u	u	o	
FRF-B	u m	u m	u m	u u	
300 ppm TDS Water					
FRF-A	u m	m	u m	u u	
FRF-B	u m	m	u m	u u	

* u = Unmodified surfactant (see text)
m = Modified surfactant (see text)
o = No microemulsions formed with either surfactant

Some of the commercial diesel fuel samples of Table 9 were investigated for fuel component effects on surfactant requirements in a different way. With each fuel, a FRF-A type of composition was prepared using either unmodified or modified surfactant. The composition also contained varying amounts of C_9+ aromatics*, and a low-aromatic-content hydrocarbon solvent (trade name, LPA) which also serves as the solvent in as-received AM-1 antimist agent. Properties of these solvents are summarized in Table 10.

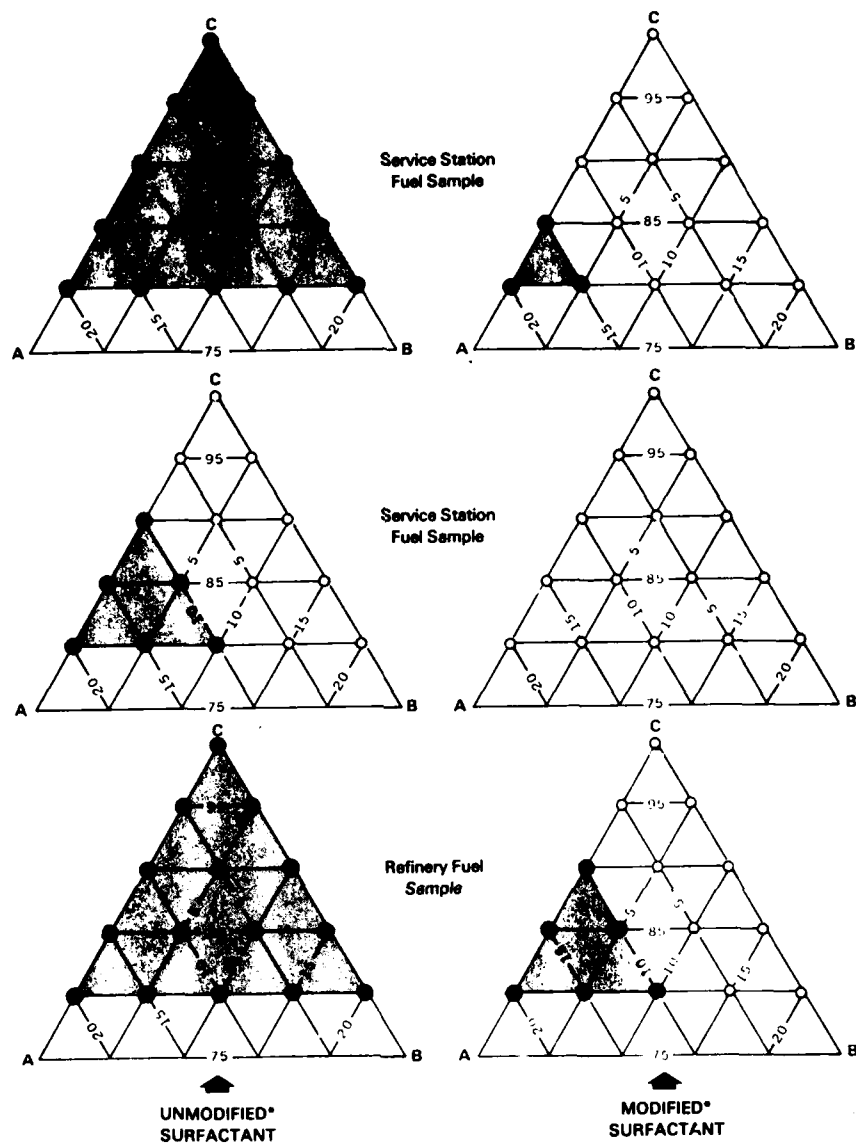
TABLE 10. ANALYTICAL DATA ON C_9+ AROMATICS AND LPA

Property	C_9+ Aromatics	LPA
Density @ 20°C, g/ml	0.875	0.806
Flash Point, °C	47	62
Refractive Index @ 20°C	1.5006	---
Hydrocarbon Type,		
FIA, vol%		
Saturates	Nil	98
Olefins	Trace	Nil
Aromatics	100	1.2
HPLC, wt%		
Aromatics	100	---
Aromatic Ring		
Carbon, wt% (UV)		
mono-nuclear	60.36	---
di-nuclear	1.36	---
tri-nuclear	0.05	---
Total	61.77	---
Distillation, ASTM D 86, °C		
IBP	160	188
10%	162	---
50%	164	221
90%	170	---
95%	173	---
EP	190	270

The results of this study are graphically illustrated for three of these fuels in Figure 17. In this figure, open circles signify macroemulsions, or phase separation, whereas filled-in circles denote transparent-to-translucent micro-emulsions.

The results presented in Figure 17, supplemented by experiments with other base fuels, indicated that the use of C_9+ aromatics might broaden the "win-

* C_9+ heavy ends from benzene-toluene-xylene production.



NOTES
Closed Circles - Microemulsions
Open Circles - Phase Separation
6 vol% Surfactant, 10 vol% Deionized Water
*See Text
A = C ₉ + Aromatics
B = LPA
C = Diesel Fuel
Numbers Denote vol% of Each Component

FIGURE 17. EXAMPLE OF FUEL COMPOSITION EFFECTS ON SURFACTANT EFFECTIVENESS

dow" of base fuel compositions in which the candidate surfactants could form aqueous microemulsions. To further investigate this indication, additional experiments were conducted in which mixtures of unmodified surfactant and C_9+ aromatic blending stock were made at volume ratios of 1:1 and 1:2. These mixtures were used in FRF-A formulations with 10 percent deionized water, in the twelve different diesel fuels of Table 9. All of the base fuels yielded microemulsions with either the 1:1 or 1:2 surfactant: C_9+ aromatics mixtures.

In addition, the aromatic hydrocarbon content of four commercial diesel fuels was varied by the addition of " C_9+ aromatics" and the emulsifier requirements were determined with deionized water containing FRF-A type composition. The four base fuels were selected according to their total aromatic ring carbon (TARC) content: Fuels Nos. 7910 and 7912 have low TARC (14.1 and 13.0 wt%, respectively), No. 7931 has high TARC (22.8 wt%), while Fuel No. 7907 has a medium-level TARC content (18.2 wt%). The C_9+ aromatics had a TARC content of 61.8 wt%. The unmodified and modified surfactant were used in all compositions, encompassing TARC contents between 13 to 31 wt%. Within these limits, unmodified surfactant did not fail to produce a microemulsion with deionized water if the TARC content of the total fuel (i.e., diesel base fuel plus C_9+ aromatics) was at least 16 wt%. A corresponding value using modified surfactant is 20 wt% TARC. In the future, other fuels will be examined similarly, and tap water will be included in the experimental matrix.

A second batch of C_9+ aromatics was purchased from the supplier of the first batch. When these two batches were compared, it was found that their infrared spectra were not identical. However, their total aromatic ring carbon contents, as determined by ultraviolet spectroscopy, were very close: 61.8 wt% for the old batch, 60.2 wt% for the new one. The performance of the two batches in FRF formulations appears to be identical.

There was concern in regard to the effect of C_9+ aromatics on the cetane number, since aromatic compounds have high octane numbers and correspondingly low cetane numbers. Cetane numbers were measured on the referee-grade diesel fuel base stock and on FRF-A made with and without 6 vol% aromatic blending stock. The values were 48, 41, and 40, respectively.

C. Viscosity

Kinematic viscosity measurements (ASTM D 445) were made on the referee grade diesel fuel and on FRF-A and FRF-B at -10°, 0°, 20°, 40°C, and the results are shown in Table 11. No problems were encountered at 20° and at 40°C. However, at 0° and at -10°C, repeatable data could not be obtained on either FRF-A or FRF-B. Increasing the samples' "soak time" in the cold baths resulted in lower apparent viscosities in most, but not all cases. Substantial day-to-day variations in the data were also observed. The worst case of reproducibility was noted in the case of FRF-A at -10°C where data obtained varied from a "no flow" condition down to a minimum of about 56 cSt. The same fuel blend at 0°C gave a variation between 156 and 22 cSt. Variations in the case of FRF-B ranged between 42 and 93 cSt at -10°C, and between 17 to 25 cSt at 0°C. Based on these yet-to-be explained irregular results, it appears that ASTM D 445 method for measuring kinematic viscosity is not applicable to FRF-type formulations at low temperatures, and future FRF research will address this problem.

D. Corrosion Characteristics

As shown in Table 8, neither FRF-A, FRF-B, nor the referee-grade base fuel is corrosive to steel. However, Ref. No. 2* diesel fuel (AFLRL Code No. 7124) used as base fuel prior to receipt of the referee-grade fuel (AFLRL Code No. 7225) did not receive an A rating in the NACE (TM-01-72) pipeline corrosion test. Typical polished steel specimens used in the NACE test are shown in Figure 18.

Significant corrosion is evident on the specimen exposed to Ref. No. 2 base fuel whereas no corrosion effects are exhibited by the specimen exposed to FRF made from Ref. No. 2 base fuel.

Even though ASTM D 130 copper strip corrosion test indicated no incompatibilities of FRF-A or FRF-B with copper (Table 8), engine laboratory experience revealed that brass is significantly attacked when exposed to FRF-A being

* Federal Test Std. 791b, Method 341.4.

TABLE 11. KINEMATIC VISCOSITY AT VARIOUS TEMPERATURES

Referee-Grade Base Fuel	Kinematic Viscosity, cSt											
	-10°C			0°C			20°C			40°C		
	1 (1)	2 (1)	3 (1)	1 (1)	2 (1)	3 (1)	1 (1)	2 (1)	3 (1)	1 (1)	2 (1)	3 (1)
7.33	---	---	---	5.24	---	---	3.12	---	---	2.11	---	---
N.F. (3)	66.0	---	100.2	155.9	158.3	---	5.43	6.35	5.30	3.48	3.53	3.46
N.F. (3)	66.6	---	96.9	153.0	170.0	---	5.42	6.32	5.30	3.48	3.53	3.46
	67.6	---	86.2	145.8	---	---	5.42	6.31	5.29	3.47	3.53	3.46
Soak Time (4):												
2 hours												
			77.6	---	---	35.9	---	---	---	---	---	---
			71.0	---	---	34.6	---	---	---	---	---	---
			65.7	---	---	34.0	---	---	---	---	---	---
			63.3	---	---	33.3	---	---	---	---	---	---
4 hours												
			78.0	---	---	24.0	---	---	---	---	---	---
			70.8	---	---	23.7	---	---	---	---	---	---
			68.9	---	---	22.5	---	---	---	---	---	---
			68.2	---	---	22.4	---	---	---	---	---	---
			67.2	---	---	22.3	---	---	---	---	---	---
16 hours												
			61.3	---	---	---	---	---	---	---	---	---
			55.5	---	---	---	---	---	---	---	---	---
			56.5	---	---	---	---	---	---	---	---	---
			58.1	---	---	---	---	---	---	---	---	---
			62.7	---	---	---	---	---	---	---	---	---
FRF-B												
	43.2	83.1	---	17.0	25.1	---	9.56	10.42	---	6.28	6.84	---
	42.1	81.4	---	17.0	25.0	---	9.56	10.43	---	6.35	6.84	---
	41.6	77.4	---	---	24.8	---	---	---	---	6.34	6.85	---
FRF-B plus 3 vol% C ₉ + aromatics												
	---	24.6	---	---	170.3	---	---	---	---	---	6.55	---
	---	24.4	---	---	170.9	---	---	---	---	---	6.55	---
	---	24.4	---	---	170.6	---	---	---	---	---	6.55	---

Notes: 1 = Different days
 2 = Average data from three independent, repeatable determinations
 3 = No flow
 4 = Standard soak time is 15 minutes



FIGURE 18. PHOTOGRAPH OF POLISHED STEEL SPECIMENS FROM NACE PIPELINE CORROSION TEST COMPARING BASE FUEL SPECIMEN (LEFT) WITH FRF SPECIMEN (RIGHT)

recirculated at 57°C. This incompatibility of the surfactant with brass undoubtedly results from complex-forming reactions between the amine functional group in the surfactant and the copper in brass.

In order to more fully document this potential problem area, a corrosion study was conducted which included a matrix of 56 combinations of surfactant composition, water composition, metal alloy, and exposure temperature. Results are presented in Table 12. Seven different metals were exposed (partly submerged) at 25° and at 77°C for 96 hours. These included carbon steel, aluminum, aluminum alloy, electrolytic copper, yellow brass, red brass, and

TABLE 12. 96-HOUR COMPATIBILITY TEST OF FRF-A WITH ALLOYS

Metal	UNS No.	T, °C ¹	Composition % vol				Wt Change ²		Rating ^{3,4}		Dissolved Metal	
			EA-8	EA-37	H ₂ O	Tap	mg	%	Emulsion	Appearance	in FRF, wt%	Zn
Steel	G10100	25	--	--	--	--	-0.3	0.00	1	A	0	0
		25	6	--	10	--	-0.5	0.00	T	A	0	0
		25	--	6	10	--	-0.2	0.00	1	A	0	0
		25	--	6	--	10	-0.2	0.00	1	A	0	0
		77	--	--	--	--	0.0	0	1	A	0	0
		77	6	--	10	--	0.0	0	5	A	0	0
		77	--	6	10	--	-0.4	0.00	5	A	0	0
		77	--	6	--	10	-0.3	0.00	5	A	0	0
Aluminum	A91100	25	--	--	--	--	+0.9	0.03	1	A	0	0
		25	6	--	10	--	+0.7	0.02	T	A	0	0
		25	--	6	10	--	+0.7	0.02	1	A	0	0
		25	--	6	--	10	+0.9	0.03	1	A	0	0
		77	--	--	--	--	+1.0	0.03	1	A	0	0
		77	6	--	10	--	+1.8	0.05	5	A	0	0
		77	--	6	10	--	+1.1	0.03	5	A	0	0
		77	--	6	--	10	+1.0	0.03	5	A	0	0
Al Alloy	A92024	25	--	--	--	--	+0.1	0.00	1	A	0	0
		25	6	--	10	--	+0.6	0.01	T	A	0	0
		25	--	6	10	--	0.0	0	1	A	0	0
		25	--	6	--	10	+0.6	0.01	1	A	0	0
		77	--	--	--	--	0.0	0	1	A	0	0
		77	6	--	10	--	+0.8	0.01	5	A	0	0
		77	--	5	10	--	+0.5	0.01	5	A	0	0
		77	--	6	--	10	+0.2	0.00	5	A	0	0
Copper	C11000	25	--	--	--	--	0.0	0	1	A(D)	0	0
		25	6	--	10	--	-7.2	0.03	2	B	0.087	0
		25	--	6	10	--	-6.3	0.03	1	B	0.080	0
		25	--	6	--	10	-7.4	0.03	2	B	0.093	0
		77	--	--	--	--	0.0	0	1	A(D)	0	0
		77	6	--	10	--	-4.9	0.02	5	B	0.103	0
		77	--	6	10	--	-2.7	0.01	5	B	0.030	0
		77	--	6	--	10	-8.4	0.04	5	B	0.103	0
Yellow Brass	C26000	25	--	--	--	--	+0.1	0.00	1	A(D)	0	0
		25	6	--	10	--	-10.7	0.05	2	C	0.102	0.023
		25	--	6	10	--	-9.4	0.04	2	C	0.073	0.015
		25	--	6	--	10	-8.7	0.04	2	C	0.075	0.018
		77	--	--	--	--	-0.1	0.00	1	A(D)	0	0
		77	6	--	10	--	-12.9	0.06	5	C	0.106	0.030
		77	--	6	10	--	-12.3	0.06	5	C	0.108	0.040
		77	--	6	--	10	-4.2	0.02	5	C	0.035	0.013
Red Brass	D2300	25	--	--	--	--	0.0	0	1	A(D)	0	0
		25	6	--	10	--	-9.4	0.08	T	B	0.091	0.010
		25	--	6	10	--	-5.8	0.05	1	B	0.062	0.008
		25	--	6	--	10	-9.8	0.08	1	B	0.103	0.013
		77	--	--	--	--	-0.2	0.00	1	A(D)	0	0
		77	6	--	10	--	-14.7	0.13	5	C	0.173	0.020
		77	--	6	10	--	-12.6	0.11	5	C	0.138	0.018
		77	--	6	--	10	-14.1	0.12	5	C	0.145	0.015
Bronze	C8360	25	--	--	--	--	+3.2	0.01	1	A(D)	0	0
		25	6	--	10	--	+37.2	0.16	T	B	0.091	0
		25	--	6	10	--	+21.3	0.10	1	B	0.095	0
		25	--	6	--	10	+5.4	0.02	T	B	0.180	0
		77	--	--	--	--	+19.3	0.09	1	A(D)	0	0
		77	6	--	10	--	+8.3	0.03	5	C	0.132	0
		77	--	6	10	--	+11.9	0.05	5	C	0.144	0
		77	--	6	--	10	+42.6	0.19	5	C	0.143	0

1 = Exposure temperature

2 = Weight change of metal coupon (+ means weight gain of coupon)

3 = Rating of emulsion:

1. Transparent

2. Translucent

3. Whitish-brown emulsion

4. Whitish Emulsion

T. Contains a trace of cream

5. Contains cream (< 2% vol)

6. Two or more layers

4 = Appearance of emulsion:

A = Unaffected

B = Bluish-green

C = Dark green

D = Black precipitate at bottom of container

5 = By X-ray fluorescence spectroscopy on exposed fuels. Among XRF active elements, only sulfur was detectable in the base fuel and in blank FRF blends.

bronze. Only the copper and copper alloy specimens corroded. This corrosion was accompanied by discoloration of both the metal and the fuel, with fuel colors ranging from blue to dark green. As would be expected, the higher temperature exposure yielded higher corrosion rates, especially on the vapor phase portion of the specimen.

Subsequent studies, which are not yet complete, demonstrated that this incompatibility with copper and copper alloys can be alleviated by the addition of an aryltriazole to the FRF formulation at a concentration of 1000 ppm. The lowest effective concentration of this type of additive is presently being determined.

Preliminary results on elastomer compatibility with FRF were obtained by MERADCOM, and these are presented in Appendix B. Among nine elastomers studied, only urethane ester failed (at 71°C).

A limited microbiological evaluation of FRF and its ingredients was conducted by NATIC, and these are summarized in Appendix C. Both the modified and unmodified surfactants proved to possess excellent biostatic properties.

E. Engine Compatibility

1. Performance in Laboratory Diesel Engines

In the discussion that follows, two measures of fuel performance are used. The change in horsepower produced by the fuel was determined by operating the engine at a fixed speed and rack setting (volumetric fuel delivery rate) and measuring any difference in horsepower when changing from the reference fuel to the microemulsion. This change in horsepower is a measure of the loss of maximum power and would appear in a vehicle as a loss in maximum acceleration or grade-climbing ability. This power loss would not be apparent during cruising operations because the driver would compensate for the power loss by increasing the fueling rate, if possible. However, the increase in fueling rate would be reflected as an increase in fuel consumption and loss in vehicle range before refueling.

This loss in vehicle range was estimated by operating the engine at a fixed speed and power output and measuring the increase in fuel rate. This is expressed as volumetric brake specific fuel consumption (BSVC) with units of gallons of fuel per horsepower-hour (gallons per unit work). Both of these measures of engine/fuel performance are dependent on a variety of engine operating variables such as degree of injection advance, rate of fuel delivery and spray characteristics.

Variable load tests were conducted with FRF-A in the CLR research engine. The resulting data, which are presented in Table 13 and Figures 19-21, indicated no significant differences in brake specific energy consumption (BSEC)* from near idle to full loads at 1500 and 3000 rpm. Up to 50-percent reductions in smoke were indicated under full load operation, but NO_x comparisons were inconclusive. Unburned hydrocarbons were generally higher,

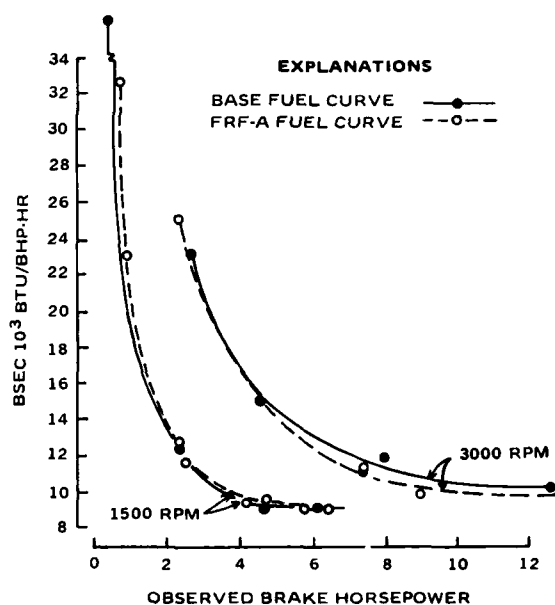


FIGURE 19. AFLRL CLR FUEL CONSUMPTION TESTS

* Brake specific consumption of the fuel's net energy of combustion.

TABLE 13. AFLRL SINGLE-POINT CLR TEST DATA

Test No.	Fuel Code	Eng. Speed, rpm	Torque, lb-ft	Observed Hp	Fuel Rate, lb/hr	BSEC, Btu/Hp-Hr	Smoke, % Opac	Exhaust, °F	Fuel Rate, 10^3 Btu/Hr	NO, ppm	NO _x , ppm	UBH, ppm	CO, %
1	BASE	1500	21.5	6.4	3.07	9,111	5.0	870	55.9	538	560	1192	0.045
2	FRF-A	1500	20.25	5.78	3.28	8,989	2.5	800	52.0	550	614	879	0.016
3	FRF-A	1500	22.5	6.44	3.65	8,978	---	870	57.8	517	595	1246	0.033
4	BASE	1500	16.25	4.64	2.30	9,032	1.0	705	41.9	470	536	391	0.0075
5	FRF-A	1500	14.75	4.21	2.50	9,407	0.5	640	39.6	462	542	423	0.0075
6	FRF-A	1500	16.5	4.71	2.86	9,619	1.5	718	45.3	464	545	613	0.012
7	BASE	1500	8.0	2.28	1.53	12,228	0.05	519	27.9	277	312	276	0.008
8	FRF-A	1500	8.75	2.50	1.82	11,532	0.01	523	28.8	282	342	323	0.011
9	FRF-A	1500	8.0	2.28	1.84	12,784	0.05	420	29.1	247	296	363	0.012
10	BASE	1500	1.0	0.29	0.81	50,896	0	375	14.8	96	132	321	0.009
11	FRF-A	1500	3.0	0.86	1.24	22,840	0	400	19.6	100	143	469	0.015
12	FRF-A	1500	2.0	0.57	1.17	32,516	0	390	18.5	106	148	446	0.012
13	BASE	3000	21.75-22.5	12.4-12.9	7.00	10,123	5.0	1170	127.6	666	740	387	0.042
14	FRF-A	3000	22.5	12.9	8.06	9,898	3.0	1100	127.7	727	824	681	0.043
15	FRF-A	3000	3.75	2.14	3.37	24,946	1.0	585	53.4	162	218	375	0.012
16	FRF-A	3000	13.0	7.43	5.24	11,172	2.0	820	83.0	378	445	458	0.008
17	BASE	3000	13.0	7.43	4.54	11,134	1.5	845	82.7	407	476	420	0.018
18	BASE	3000	4.0	2.28	2.88	23,017	1.0	619	52.5	186	232	285	0.008
19	BASE	3000	7.5	4.28	3.52	14,986	1.0	700	64.1	238	277	272	0.008
20	BASE	3000	14.0	8.00	5.24	11,935	1.5	910	95.5	461	552	421	0.009
21	FRF-A	3000	15.75	9.00	5.63	9,909	0.05	860	89.2	510	614	468	0.008

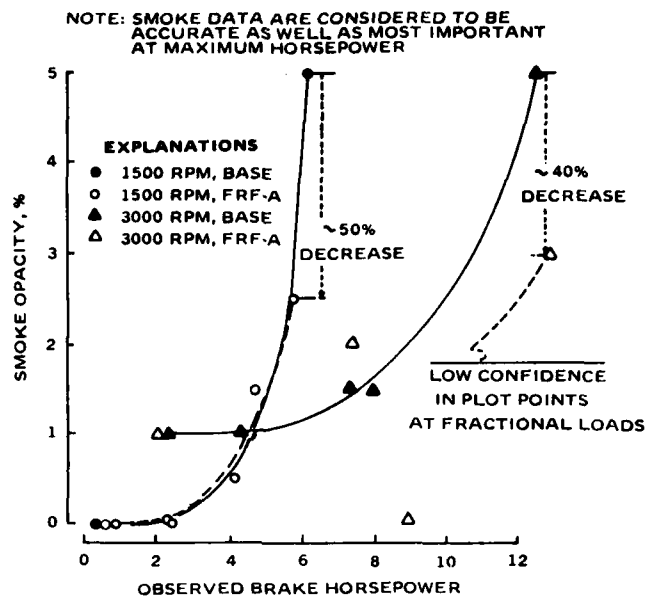


FIGURE 20. AFLRL CLR ENGINE SMOKE TESTS

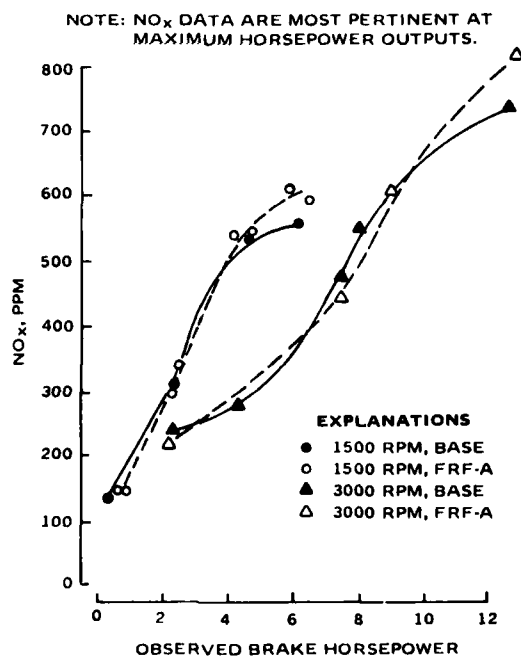


FIGURE 21. AFLRL CLR ENGINE NO_x TESTS

and carbon monoxide emissions data were inconclusive. Particulate and carcinogenic emissions were not investigated.

The initial performance evaluations in the previously described two-cycle multicylinder engines showed that the engines could be operated satisfactorily with both of the FRF formulations. These engines suffered a 6.5 ± 1.5 percent power loss and an 11.5 ± 2.5 percent increase in BSVC with the FRF-A. The normally aspirated DD3-53 engine suffered a greater loss in maximum power but less of an increase in BSVC (loss in vehicle range) than the turbocharged 6V-53T engine.

The FRF-B, which was only evaluated in the DD6V-53T engine, showed no significant loss in power ($-0.8 \pm 1.5\%$) at full-rack conditions, but had an increase in BSVC of 6.8 ± 2.3 percent at constant load conditions. No statistically significant change in thermal efficiency occurred with any combination of fuel or two-cycle engine.

Exhaust emissions measurements were made with the DD3-53 engine using FRF-A only. These results indicated a 9 ± 2 percent reduction in oxides of nitrogen, a 120 ± 50 percent increase in unburned hydrocarbons and range of change in carbon monoxide emissions from +12 to -80 percent.

Both FRF-A and FRF-B were evaluated in the LD-465 engine, with no attempt being made to defeat or adjust the density compensator section of the fuel injection pump. This engine fuel injection pump is equipped with a density compensation unit which adjusts the full load fuel delivery based on the fuel viscosity. This automatic adjustment is based on normal hydrocarbon fuel density-viscosity relationships and is to prevent overfueling as the fuel supply is changed. This system was left intact and probably accounts for the larger loss in maximum power with the FRF since these fuels have a different viscosity-density relationship than anticipated in the fuel injection pump design.

The FRF-A suffered a 11 ± 6 percent loss in maximum power and a 10 ± 3 percent increase in BSVC.

With FRF-B as the fuel, the engine showed an average 9 ± 5 percent loss in power and an average 2 ± 4 percent increase in BSVC. As evidenced by the large standard deviations with these last two figures, the engine was more erratic in operation with the FRF-B than with other fuels.

For performance evaluations in the AVDS-1790 single-cylinder assembly (CUE-1790), the specified fuel consumption is for the reference diesel fuel and establishes the test load (IMEP). The test fuels were first evaluated at the rack setting (volumetric fuel flow rate) established with the reference fuel. This determined the power loss associated with each of the test fuels. The rack was then adjusted to obtain the same IMEP as the reference fuel, and the BSVC change was measured.

The performance data from the CUE-1790 can be expressed either on an indicated or brake (observed output) basis. For a single-cylinder engine, the friction load can be a larger percentage of the total output of the engine, so that indicated performance is often a better way of examining the performance data. However, this basis would tend to understate percentage values if comparisons are made to brake values of multicylinder engines. As a result, both brake and indicated power comparisons are given in Table 14.

TABLE 14. CUE-1790 PERFORMANCE COMPARISON AT
1800 RPM WITH REFEREE-GRADE BASE FUEL

	FRF-A	FRF-B
Change in BHP, %	-7 ± 0.5	1 ± 0.5
Change in IHP, %	-6 ± 0.5	1 ± 0.4
Change in BSVC, %	20 ± 2	12 ± 1
Change in ISVC, %	18 ± 2	12 ± 1

The overall performance of the two fuels are summarized in Figures 22 and 23. The fuel performance based on differences in heating value is indicated by the lines labeled "calculated." Except for the LD-465 engine, in which the injection pump "disturbs" the full rack setting, all of the

engines produced more power at full rack than would be anticipated.

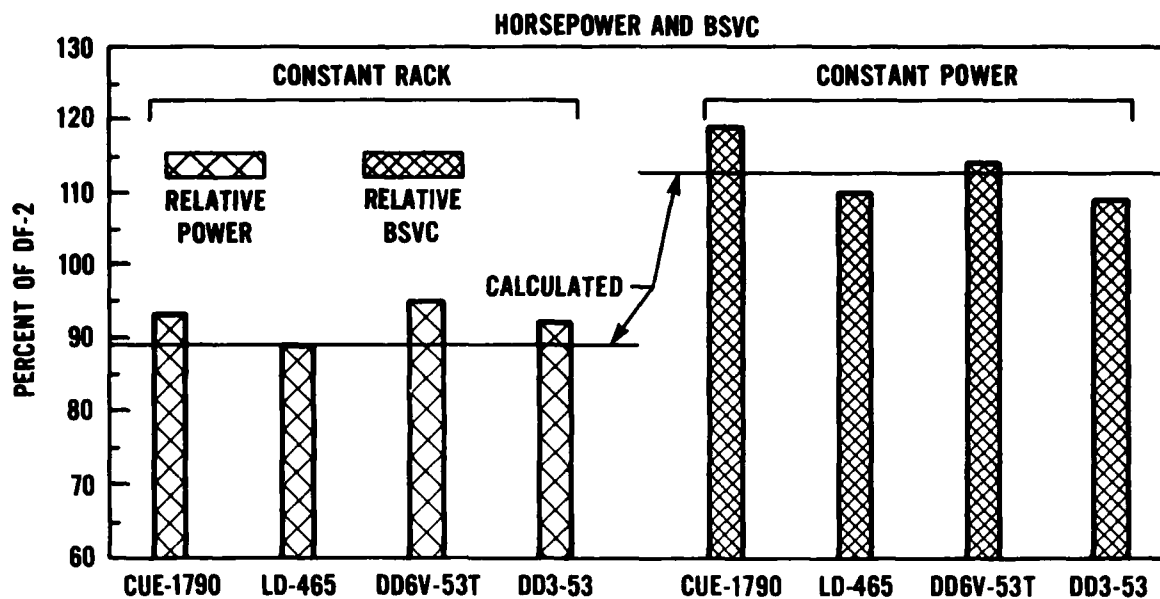


FIGURE 22. PERFORMANCE OF FRF-A VERSUS REF. DF-2

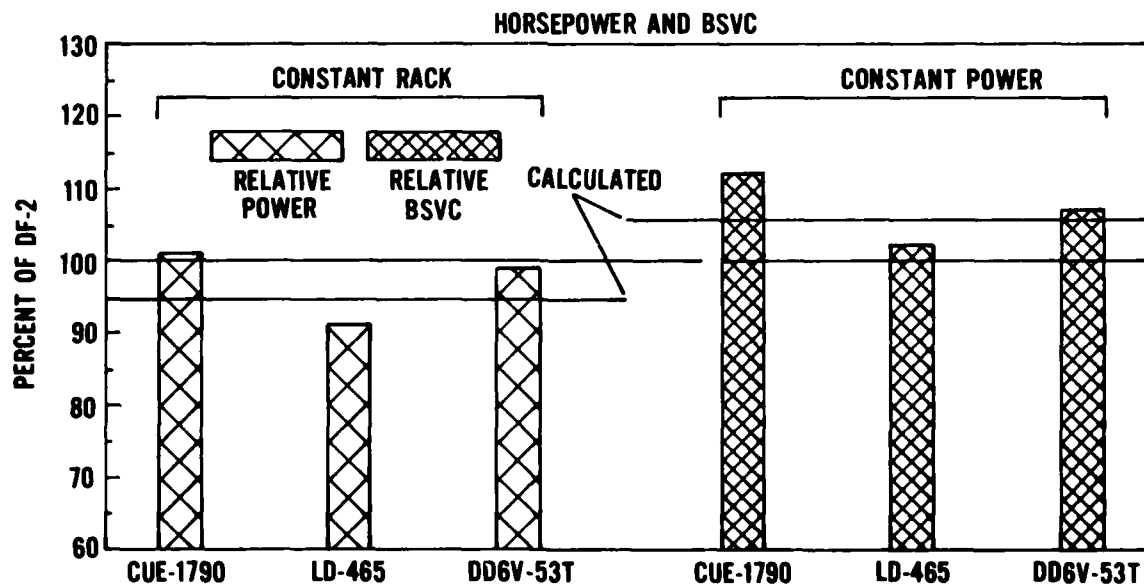


FIGURE 23. PERFORMANCE OF FRF-B VERSUS REF. DF-2

This may be due in part to the 60- to 200-percent increase in fuel viscosity which could reduce leakage at the injector plunger and nozzles and increase the amount of fuel delivered to the cylinder. The increases in BSVC do not show such a clear trend, and the differences between the actual and expected results may be due to injection system and engine response differences.

Relative to diesel fuels, both of these fuels had different viscosities and densities which would affect the fuel injector spray characteristics. Also, since the heating values of the fuels were lower than diesel fuel on a volumetric basis, the Btu's per crank angle degree delivered to the combustion chamber would be reduced when changing from diesel fuel to the FRF. If, for example, the beginning of injection was the controlled timing variable, then at a constant load (approximately equal Btu input rate), the FRF would begin to be injected at the same point in the cycle as the diesel fuel, but the Btu input rate would be slower (less Btu/°CA) and the duration of injection would increase. The sensitivity of the combustion system to such changes would influence the performance of the FRF in that engine.

A brief evaluation of FRF-A performance relative to the referee-grade base fuel was conducted in a Caterpillar 1-G2 test engine. The results, which are presented in Table 15, indicate that the mechanical design and operating

TABLE 15. PERFORMANCE OF FRF-A IN CATERPILLAR SINGLE-CYLINDER
ENGINE RELATIVE TO REFEREE-GRADE BASE FUEL
[Federal Test Standard 791B, Method 341]

Change in Brake Power, %	-11.2
Change in Brake Specific Volumetric Fuel Consumption, %	+17.7
Change in Thermal Efficiency of Work Cycle, abs %	- 1.6

conditions of this engine are not optimum for FRF-A. In fact, this engine was the only one among those used for FRF evaluation that produced higher temperature exhaust gases than did the referee-grade base fuel.

During these laboratory engine evaluations, it was often observed that detergency action by the FRF cleansed previously-used fuel-handling systems,

resulting in filter fouling during initial operations. In such cases, no further difficulties were encountered after replacement of the fouled filters. No such problems were encountered when using new fuel-handling equipment.

2. CUE-1790 Endurance Tests

In this program, three 250-hour endurance tests were conducted with the CUE-1790 single-cylinder engine to begin to evaluate the deposition and wear tendencies of the FRF-A emulsion. One test was conducted using the reference fuel and the other two tests were with two formulations of FRF-A. A summary of the operating conditions and test results is given in Table 16,

TABLE 16. OPERATING SUMMARY FOR 250-HOUR ENDURANCE TESTS
WITH THREE NEW CUE-1790 CYLINDER ASSEMBLIES

Cylinder Assembly No.	1	2	3
Fuel	Referee-Grade	FRF-A	FRF-A
Engine Speed, rpm	1805	1803	1800
Load, N-m (lb-ft)	176(130)	173(128)	184(136)
Avg Friction Load, N-m (lb-ft)	46(34)	52(38)	30.6(22.6)
Observed Power, kW (hp)	33.3(44.6)	32.7(43.9)	34.8(46.7)
Indicated Power, kW (hp)	41.9(56.2)	42.4(56.9)	40.6(54.4)
Fuel Rate, kg/hr lb/hr	8.48(18.7)	9.48(20.9)	9.75(21.5)
ISFC, lb/IHP-hr	0.333	0.367	0.395
ISVC, gal/IHP-hr	0.0472	0.0506	0.0595
Indicated Thermal Efficiency	41.9	44.0	40.3
Exhaust Emissions			
NO, ppm	662	580	867
NO _x , ppm	685	591	892
UBH, ppm carbon	176	243	415
CO, %	0.20	0.24	0.17

and detailed test reports are presented in Appendices D, E, and F. The test with the reference fuel was used as the standard to establish the indicated power level to be obtained with the FRF tests. The indicated power was determined from the engine friction which was measured twice daily by monitoring the engine at the normal operating temperatures. The friction was found to be very stable throughout each test period but varied considerably with each engine assembly.

Test No. 2, the first of the FRF-fueled tests, had a slight increase in engine friction and thus a lower observed power. The exhaust emissions were measured periodically throughout the test (Table 16) and agreed with emissions results observed during the previously discussed short-term performance tests. There was a slight decrease in BSFC during the test, and the average indicated thermal efficiency during the test was higher than that observed during the reference fuel test.

The third test was also conducted with FRF-A. This engine assembly had significantly lower friction than the previous two tests, and the performance, particularly the exhaust emissions, seemed to indicate that the injection behavior was different than the previous two tests. However, subsequent injector tests and engine-part measurements failed to reveal any abnormalities. The indicated thermal efficiency for this test was slightly lower than that observed in the reference fuel test.

The post-test inspections and ratings of the cylinder components showed no unusual wear or major differences in deposits. The piston deposits from the two FRF tests are equal and, in some instances, lower than those of the first test. No noticeable effects resulted from the mineral content of the tap water (approximately 300 ppm total dissolved solids) used in forming the emulsions for Test No. 3. The appearance of injector nozzle holes and pintels are shown in the photographs of Figures 24 and 25. No hole enlargement occurred in any case, and some spalling of the normal carbonaceous deposits was evident, but only in the FRF-fueled tests. The only significant difference in appearance among the pintels of Figure 25 is the presence of black deposits on the tip but only in the water-free base fuel test.

As a result of the observed differences between Test No. 3 and the preceding two tests, a performance comparison test was made with referee-grade base fuels immediately after the third 250-hour test. The results are presented in Table 17 where it can be noted that the indicated thermal efficiency is the same with either fuel but the exhaust emissions are not as different between the two fuels as would be expected.



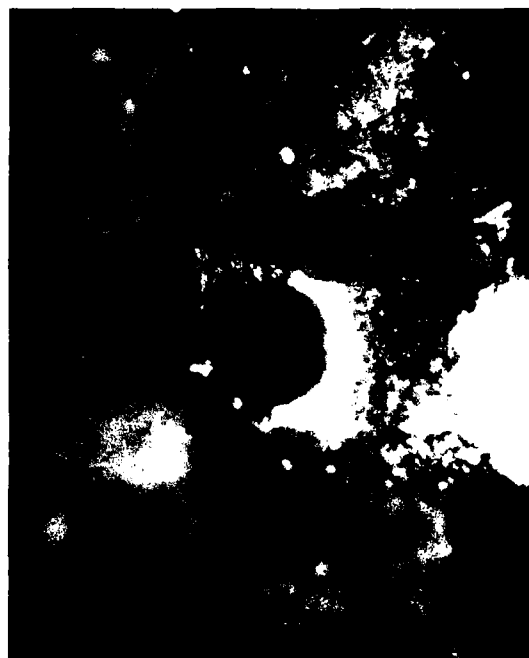
Typical Hole in New Nozzle



Typical Hole in Nozzle from Test No. 1
[Neat Referee-Grade Base Fuel]



Typical Hole in Nozzle From Test No. 2
[FRF-A with Deionized Water]



Typical Hole in Nozzle From Test No. 3
[FRF-A with Tap Water (~300 ppm TDS)]

FIGURE 24. PHOTOGRAPHS OF NEW AND USED INJECTOR NOZZLE
HOLES FROM CUE-1790 ENDURANCE TESTS

TABLE 17. PERFORMANCE COMPARISON OF CUE-1790
CYLINDER ASSEMBLY NO. 3

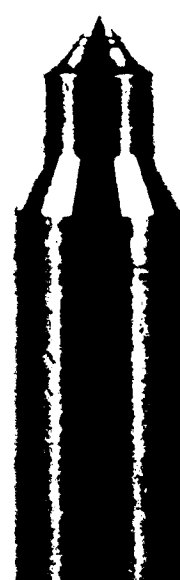
Fuel	Referee-Grade	FRF-A
Engine Speed, rpm	1800	1800
Load, N-m (lb-ft)	184(136)	184(136)
Friction Load, N-m (lb-ft)	31.2(23)	30.6(22.6)
Observed Power, kW (hp)	34.7(46.6)	34.8(46.7)
Indicated Power, kW (hp)	40.6(54.4)	40.6(54.4)
Fuel Rate, kg/hr (lb/hr)	8.53(18.8)	9.75(21.5)
Heat Input Rate, Btu/hr	342,574	343,226
ISFC, g/w-hr (lb/Ihp-hr)	0.117(0.345)	0.134(0.395)
ISVC, l/kW-hr (gal/Ihp-hr)	0.139(0.0491)	0.154(0.0546)
Indicated Thermal Efficiency, %	40.5	40.3
Exhaust Emissions		
NO, ppm	862	867
NO _x , ppm	923	892
UBH, ppm carbon	396	415
CO, %	0.237	0.173
CO ₂ , %	9.88	9.67
O ₂ , %	7.1	7.3



Pintle from Test No. 1



Pintle from Test No. 2



Pintle from Test No. 3

FIGURE 25. PHOTOGRAPHS OF PINTLES FROM INJECTORS USED IN CUE-1790
ENDURANCE TESTS

It was observed in early preliminary studies⁽¹²⁾ (and by others) that in the absence of nitrogen compounds, 10 percent water-in-fuel macroemulsions made with sugar-type surfactants resulted in significant reductions in NO_x . Hence, the similarities in NO_x emissions between FRF and its base fuel probably stem from oxidation of the nitrogen in the fuel in the form of the amide/amine surfactant.

3. Performance in Laboratory Turbine Combustor

As mentioned previously, a T-63 combustor was used to determine the combustion performance characteristics of candidate fire-resistant diesel fuel compositions. FRF-A and FRF-B were compared with neat referee-grade base fuel and Jet A, and the results are summarized in Table 18. Combustion

TABLE 18. SUMMARY OF FRF PERFORMANCE IN ALLISON T-63
TURBINE COMBUSTOR FACILITY
(37°C Inlet Air; 1.4 atm Inlet Pressure; 0.18 kg/sec Air Flow Rate)

	F/A For Ignition	Blowout		Combustion Efficiency, %		NO _x Emissions g/kg Fuel		100% Power	
		10%	100%	40%	100%	10%	100%	Flame Radiation	Exhaust Smoke
		Power	Power	Power	Power	Power	Power	(Relative to DF-2)	(Relative to DF-2)
Jet A	0.035	0.006	0.003	97.3	98.1	1.8	6.2	---	---
DF-2	0.035	0.006	0.002	96.8	98.1	---	---	100%	100%
FRF-A	0.05-0.06	0.007	0.003	93.3	98.1	6.5	10.9	65%	50%
FRF-B	---*	---*	0.009	74.2	98.1	---	---	74%	147%

* FRF-B could not be ignited directly.

performance measurements were made at six power points representing 10, 25, 40, 55, 75, and 100 percent of full power. Stability (lean blowout limit) measurements on all the fuels were made at each power point, and ignition characteristics were determined.

Ignition Measurements--The conditions for ignition were:

Inlet temperature = 37°C
Inlet pressure = 1.4 atm (20 psi)
Air Mass flow rate = 0.18 kg/sec (0.4 lb/sec)

The inlet air temperature of 37°C was the lowest temperature that could be obtained from the air preconditioning system. This temperature is difficult to control and is largely dependent on weather conditions (ambient temperature and humidity).

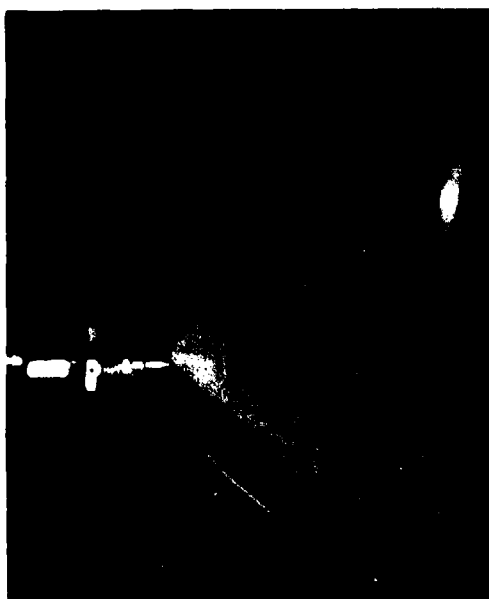
Repeatable ignition of the base fuel occurred at overall fuel/air ratios above 0.035. The FRF-A required a somewhat richer mixture (0.05 to 0.06), and the FRF-B could not be ignited. The absence of ignition with FRF-B was found to be caused by significantly degraded spray patterns resulting from negligible-to-poor atomization as shown in the photographs of Figure 26.

Stability--In general, the fuel/air ratio at which lean blowout occurs decreases as power increases. The increased stability at higher power corresponds with the improved vaporization and mixing that accompanies the higher power conditions.

It was not possible to stabilize a flame with the AM-1-containing fuel at the 10 and 25 percent power points. The fuel/air ratios for lean blowout with the AM-1-containing fuel at the higher power points were significantly higher than those of the other fuels. As in the case of the ignition problem, this may also be attributed to poor atomization.

Combustion Efficiencies and Gaseous Emissions--Combustion efficiency, as determined from measurements of gaseous emissions, increases with increasing power. At full power, each fuel gave high combustion efficiency (greater than 98.1%). However, there were significant differences between the fuels at reduced power.

Due to the nitrogen content of the surfactant, the NO_x emissions were much higher for the microemulsions than with the neat fuel. The differences were



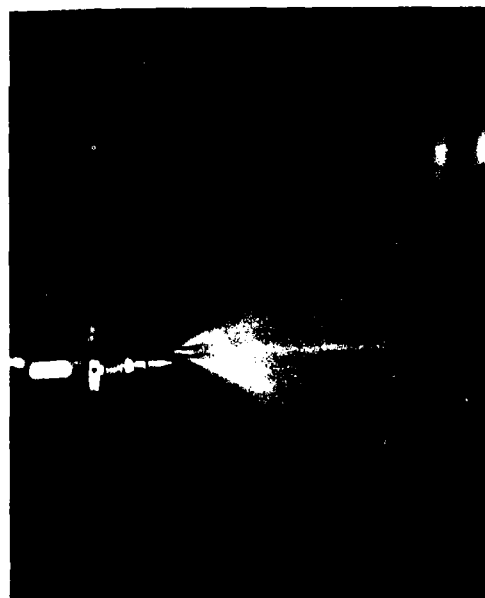
Base Fuel at 10% Power Point



FRF-B at 10% Power Point



FRF-B at 55% Power Point



FRF-B at 100% Power Point

FIGURE 26. PHOTOGRAPHS OF SPRAY PATTERNS OF FRF-B IN T-63 COMBUSTOR FACILITY

particularly evident at the low power points where the NO_x from atmospheric N_2 oxidation is relatively low. While the thermal NO_x varied, the NO_x from fuel-bound nitrogen in FRF-A was essentially constant at the various power levels.

Flame Radiation and Exhaust Smoke--The flame radiation and exhaust smoke from the microemulsion were significantly lower than that from the neat DF-2 fuel. At full power, where particulate formation is most evident, reductions of 35 percent in flame radiation and 50 percent in exhaust smoke were observed with FRF-A. In the cases of FRF-B the radiation was reduced by 26 percent, but the exhaust smoke was about 47 percent higher than that of the neat fuel. These results indicate that the antimist agent plays a role in soot formation, probably because it does not vaporize.

F. Flammability Properties

As mentioned previously, several different flammability evaluation procedures were employed to define the vulnerability characteristics of FRF candidates, and the results for referee-grade base fuel FRF formulations are summarized in Table 19. Additional flammability determinations are described in the following paragraphs.

1. Laboratory and Bench-Scale Measurements

Early in this study, it was observed that closed cup flash point measurements (ASTM D 93) were unsuccessful with FRF formulations because water vapor extinguished the pilot flame in the Penske Martens flash point apparatus. Subsequently, it was observed that some FRF samples did not display this problem. In such cases, the flash point of the FRF was about the same as that of the base fuel. No explanation has been found for such anomalous behavior. It does not seem to be related to experimental techniques, and both types of flash point results are observed.

During the previously discussed investigations of the addition of C_9^+ aromatics to FRF formulations, there was concern about the lower flash point of this blending stock. The experimental results listed in Table 20 indicate that

TABLE 19. REFEREE-GRADE-BASE-FUEL/FIRE-RESISTANT FUEL FLAMMABILITY PROPERTIES

Property	Referee Grade Base Fuel MIL-F-46162A(MR), Grade II	FRF-A: Referee Fuel Plus 10 vol% Deionized Water Plus 6 vol% Surfactant	FRF-B: Referee Fuel Plus 5 vol% Deionized Water Plus 3 vol% Surfactant Plus 0.2 vol% Antimist Agent
Flame propagation across bulk liquid surface at 77°C	Wick burning with simultaneous propagation	Wick burning only	Wick burning followed by de- layed propagation
Burns on wick at 25°C	Yes	Yes	Yes
Flammability of fuel mist at 25°C (Mist Flashback Test)	Extreme	Moderate	Nil
Ballistic tests at 77°C (20-mm HEIT)	Catastrophic fire	Transient fireball with self-extin- guishing ground fire	Diminished transient fireball only
Flash Point, °C	61	65*	---
Fire Point, °C	91	---	104
Autoignition Temperature, °C	224	405	---

* Pilot flame in Penske Martens apparatus often extinguished by water vapor.

TABLE 20. FLASH POINT OF VARIOUS FUEL FORMULATIONS

Referee-Grade Base Fuel	Volume Percent				Flash Point, ⁽¹⁾ °C
	C ₉ + Aromatics (First Batch)	C ₉ + Aromatics (Second Batch)	Unmodified Surfactant	Water (Deion.)	
100	0	0	0	0	61
---	100	0	0	0	47
---	0	100	0	0	33
84	0	0	6	10	65 ⁽²⁾
78	6	0	6	10	61
78	0	6	6	10	55 ⁽²⁾
88	0	6	6	0	52

(1) Average of three independent determinations.

(2) Occasionally no flash point could be measured with the same batch of FRF.

FRF flash point reductions stemming from the added C₉+ aromatics should not exceed 10°C.

Autoignition temperatures (ASTM D 2115-modified) of FRF samples containing varying amounts of water and surfactants have also been investigated. As shown by the data in Table 21, these evaluations showed only slight dif-

TABLE 21. SUMMARY OF AUTOIGNITION PROPERTIES OF REFEREE-GRADE-BASE-FUEL FRF FORMULATIONS OF VARIOUS WATER CONTENTS

Surfactant Content, vol%	Water Content, vol%		Mean Autoignition Temperature, ⁽³⁾ °C(°F)
	Deionized ⁽¹⁾	Tap ⁽²⁾	
0	0	0	224(435)
5	5	--	404(760)
5	10	--	427(800) [2] ⁽⁴⁾
6	10	--	416(780) [3] ⁽⁴⁾
6	--	10	399(750) [5] ⁽⁴⁾
6	--	12	396(745)
6	--	14	416(780)
6	--	16	418(785)
10	10	--	388(730)

(1) Specific conductance of <1 micromho per cm

(2) Specific conductance of 480 micromhos per cm

(3) ASTM D 2155 (modified)

(4) Number of replicate samples averaged

ferences in autoignition temperatures (AIT) with no apparent correlation with water content. However, all of the water-containing samples had substantially higher AITs than that of the base fuel, e.g., approximately 400°C vs approximately 225°C.

As mentioned in an earlier section of this report, those candidate antimist agents which were soluble in the base fuel under the conditions of the screening tests were evaluated with the AFLRL mist flashback techniques. The results, which are summarized in Table 22, reveal that none of the fuel-soluble candidates is superior to AM-1 in antimist effectiveness.

TABLE 22. MIST FLASHBACK RATINGS OF CANDIDATE ANTIMIST AGENTS*
IN REFEREE-GRADE BASE FUEL

<u>Candidate Agent</u>	<u>Concentration, wt%</u>	<u>Mist Flashback Rating, cm</u>
Base Fuel	100	20.3
AM-1	0.2	0.8
AM-3	0.5	1.3
AM-3	0.3	1.3
AM-11	0.5	7.6**
AM-12	0.5	7.2
AM-13	0.5	4.7
AM-14	0.9	0
AM-14	0.5	2.5
AM-15	0.5	1.3
AM-15	0.5	0.8
AM-15	0.2	3.0
AM-15	0.2	1.3
AM-16	0.5	0.8
AM-16	0.2	2.5

* Only the listed candidates were soluble in base fuel.

** Polymer degraded while dissolving.

The mist flashback and impact dispersion tests were used for preliminary assessment of the effects of fuel recycle in a diesel engine on mist flammability and pool-burning characteristics. The results presented in Table 23 indicate substantial recycle-induced degradation of FRF-B flammability resistance while the flammability of the recycled FRF-A is about the same as that of the virgin FRF-A.

TABLE 23. FLAMMABILITY CHARACTERISTICS OF VIRGIN AND DIESEL-ENGINE-RECYCLED FUELS

Fuel	Mist Flashback Rating, cm	Impact Dispersion Test at 77°C	
		Description	Duration of Pool Burning, sec
Base Fuel	22	Mist Fireball	100
FRF-A	17	Mist Fireball	0.6-1.2
FRF-B	0	No Fireball	0
FRF-A(1) Recycled	11	Mist Fireball	1.2(3)
FRF-A(2) Recycled	15	---	---
FRF-B(1) Recycled	6	Mist Fireball	0.6
FRF-B(2) Recycled	8	Mist Fireball	0-3.0

(1) LD465 Engine Test

(2) 6V-53T Engine Test

(3) Insufficient Sample to Test

Impact dispersion tests were conducted to develop more detailed information on the effects of surfactant content on the flammability characteristics of aqueous microemulsions, and the results are presented in Table 24. In these tests, the impact slab surface temperature was varied from 77° to 99°C, while the fuel temperature was maintained at 77°C. The FRF-A results, which are graphically portrayed in Figure 27, reveal several interesting phenomena. First, as would be expected, the duration of pool burning prior to self-extinguishment increases with increasing slab temperature; however, the pool-burning duration decreases with increasing surfactant content. This provides at least an indirect indication of the influence of water droplet size on self-extinguishment effectiveness since the size of the droplets apparently decreases with increasing surfactant content.* Furthermore, the data for 10 percent surfactant indicate a further decrease in duration of pool burning at the higher impact slab temperatures. This substantial decrease in the slope of the graphical correlation is possibly related to the fact that the FRF formulation containing 10 percent surfactant remained clear at the 77°C fuel test temperature, whereas those formulations containing 6 percent or less surfactant became opaque below 77°C, reflecting the presence of larger water droplets.

* A decrease in turbidity is observed upon increasing the surfactant-to-water ratios.

TABLE 24. SUMMARY OF AFLRL IMPACT DISPERSION/POOL BURNING
TEST RESULTS WITH FIRE-RESISTANT FUEL (FRF)
FORMULATIONS WITH REFEREE-GRADE BASE FUEL

Volume %		Wt% AM-1	Impact Slab Temp* (°C)	Temp* (°F)	Pool Fire Duration, sec
Water	Surfactant				
0	0	0	77	171	PTC**
5	2	0	77	171	15
5	2	0	77	171	8
5	3	0	77	171	15
5	5	0	77	171	2.4
5	5	0	88	190	4.2
5	5	0	93	199	
5	5	0	99	210	PTC**
8	8	0	77	171	
8	8	0	88	190	
8	8	0	99	210	
10	4	0	77	171	1.8
10	5	0	77	171	1.2
10	5	0	88	190	15
10	5	0	93	199	
10	6	0	77	171	1.2
10	6	0	77	171	0.6
10	6	0	77	171	0.9
10	6	0	77	171	0.6
10	6	0	88	190	8.4
10	6	0	88	190	9.6
10	6	0	99	210	51
10	6	0	99	210	172
10	6	0	99	210	126
10	8	0	77	171	
10	8	0	88	190	
10	8	0	99	210	
10	10	0	77	171	0.6
10	10	0	88	190	1.2
10	10	0	99	210	2.4

* Initial Fuel Temperature of 77°C.

** (PTC) Pool Totally Consumed.

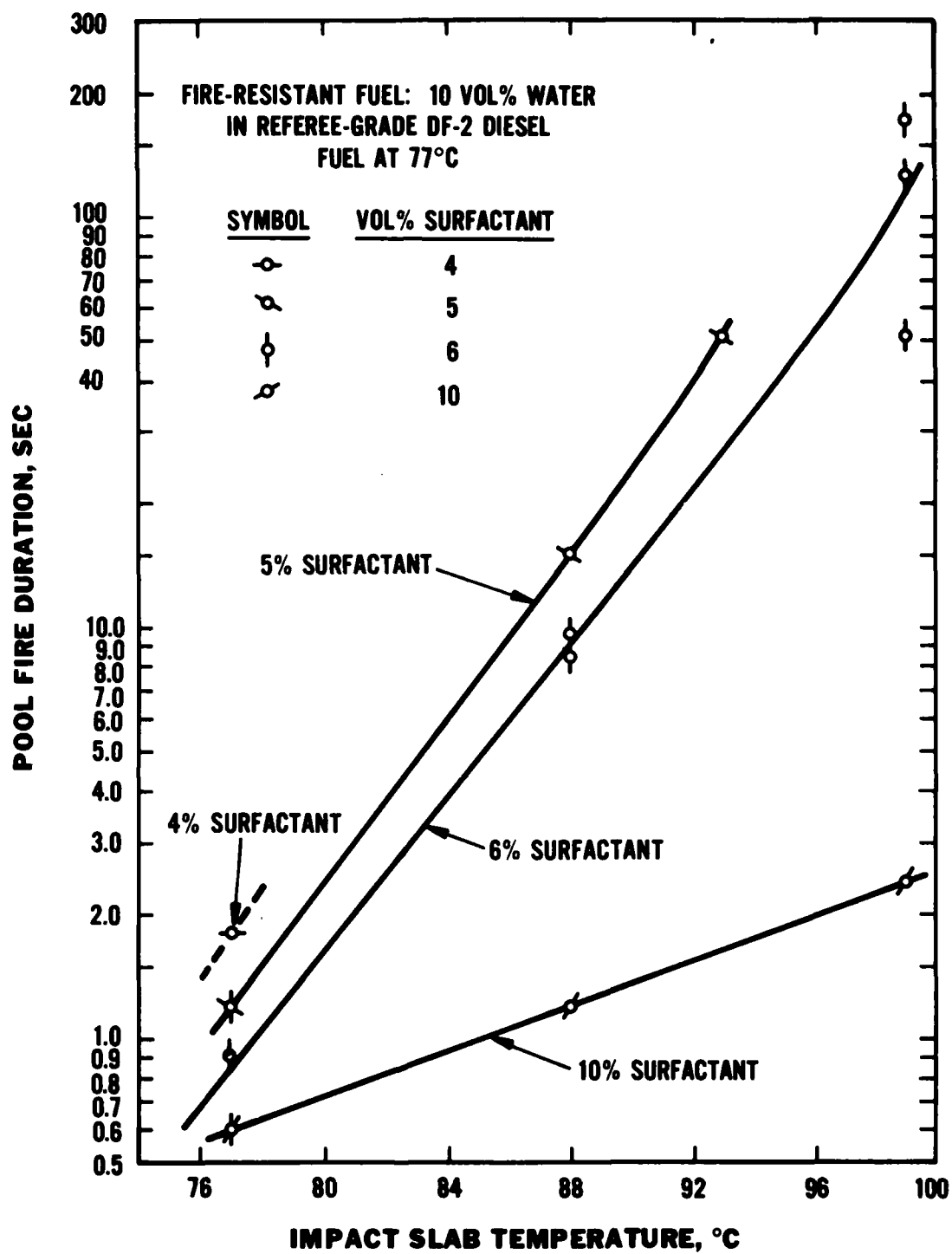


FIGURE 27. INFLUENCE OF SURFACTANT CONTENT ON IMPACT DISPERSION FLAMMABILITY OF FIRE-RESISTANT FUEL

2. Simulated Full-Scale Ballistic Tests

The previously described 20-mm high-explosive-incendiary-tracer projectile (HEIT) ballistic test was used to evaluate FRF microemulsions. Results are presented in Table 25. The object of this series of tests was to compare FRF-A and FRF-B formulations made from referee-grade base fuel (Tests 5-14) with the same formulations made from base fuel used in previous 20-mm HEIT tests (Tests 1-4). Effects of lower and higher surfactant content (Tests 15-18) and lower test temperatures (Tests 19-24) were also explored. The photographs of Figure 28a correspond to conditions of Tests 1 and 2 (or 3); and those of Figure 28b correspond to conditions of Tests 1 and 5; however, they show repeat tests which were conducted at a later time than Tests 1-5. The ballistic tests are presented in such a way, that even if total self-extinguishment was not achieved, the degree of residual pool burning can be compared between the various formulations. Comparison of results for FRF-A and FRF-B made from the two different base fuels (Tests 7-14 versus Tests 1-4) indicates that microemulsions made from the referee-grade base fuels are less fire resistant than are those made from the previously used base fuel. These differences appeared to be related to differences in base fuel volatility even though the flash points were comparable. As mentioned previously, ASTM D 86 distillation data show that the referee-grade fuel is borderline between DF-2 and arctic diesel (DF-1) in volatility distribution, whereas the previously used base fuel was a typical DF-2.

It was first established that the base fuel (Tests No. 5 and 6) had total pool burning even 3 seconds after impact, and the burning intensified as time progressed. Tests conducted with 10 percent H_2O and 5 percent surfactant (Tests No. 7 and 8) did show self-extinguishment in one test, but not in both. Tests conducted on blends containing 10 percent H_2O and 6 percent surfactant did not completely self-extinguish in any of the four tests that were conducted. It should be mentioned that in any test where pool fires continued 10 seconds past impact, self-extinguishment did not occur. It can also be seen that total self-extinguishment did not occur in every test with blends containing antimist agents. Tests Nos. 19-24 show that FRF blends with 6 percent modified surfactant and 10 percent water self-extinguish at temperatures near the flash point of the base fuel and at temperatures down to 18°C.

TABLE 25. SUMMARY OF 20-mm HEIT BALLISTIC TEST RESULTS WITH VARIOUS
FIRE-RESISTANT FUEL FORMULATIONS

Test No.	Fuel Designation	Base Fuel	Water, vol%	Surfactant vol%	Antimist Agent, wt%	Fuel Temp, °C	Pool Fire Width, m at 3 sec at 10 sec	Pool Fire Width, m at 10 sec
1	Neat	Pre-referee-grade DF-2	0	0	0	77	4.6	4.6
2	FRF-A	Pre-referee-grade DF-2	10	6	0	77	1.2	SE***
3	FRF-A	Pre-referee-grade DF-2	10	6	0	77	0.0	SE***
4	FRF-B	Pre-referee-grade DF-2	5	3	0.2	77	0.0	SE***
5	Neat	Referee-grade DF-2	0	0	0	77	4.6	4.6*
6	Neat	Referee-grade DF-2	0	0	0	77	4.6	4.6*
7	FRF-A	Referee-grade DF-2	10	6	0	77	2.4	1.0**
8	FRF-A	Referee-grade DF-2	10	6	0	77	3.1	2.4**
9	FRF-A	Referee-grade DF-2	10	6	0	77	3.7	0.6**
10	FRF-A	Referee-grade DF-2	10	6	0	77	3.1	1.2**
11	FRF-B	Referee-grade DF-2	5	3	0.2	77	0.6	SE***
12	FRF-B	Referee-grade DF-2	5	3	0.2	77	1.0	1.5**
13	FRF-B	Referee-grade DF-2	5	3	0.2	77	1.0	1.8**
14	FRF-B	Referee-grade DF-2	5	3	0.2	77	1.0	1.3**
15	---	Referee-grade DF-2	10	5	0	77	1.5	SE***
16	---	Referee-grade DF-2	10	5	0	77	2.4	2.4**
17	---	Referee-grade DF-2	10	10	0	77	1.5	SE***
18	---	Referee-grade DF-2	10	10	0	77	1.5	SE***
19	Neat	Referee-grade DF-2	0	0	0	63	2.4	3.1*
20	FRF-A	Referee-grade DF-2	10	6	0	63	1.8	SE***
21	Neat	Referee-grade DF-2	0	0	0	46	2.4	3.1*
22	FRF-A	Referee-grade DF-2	10	6	0	46	1.5	SE***
23	Neat	Referee-grade DF-2	0	0	0	18	1.5	1.2**
24	FRF-A	Referee-grade DF-2	10	6	0	18	0.0	SE***

* Self-sustaining Pool Fire

** Easily Extinguished Pool Fire

*** (SE) Self-Extinguished Pool Fire

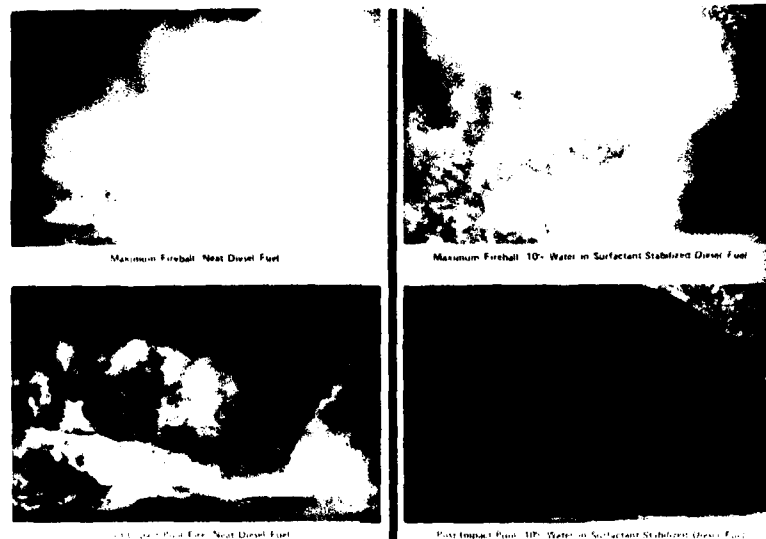


FIGURE 28a. BALLISTIC RESPONSE OF NEAT AND WATER-CONTAINING DIESEL FUELS AT TYPICAL MAXIMUM OPERATIONAL TEMPERATURE OF 77°C (170°F) [BASE FUEL FLASH POINT OF 63°C (145°F)]

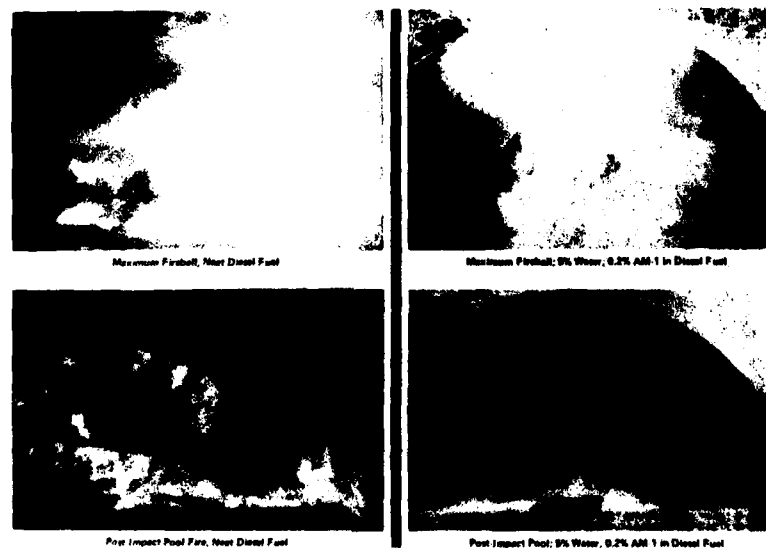


FIGURE 28b. BALLISTIC RESPONSE OF NEAT AND WATER-CONTAINING ANTIMIST DIESEL FUELS AT TYPICAL MAXIMUM OPERATIONAL TEMPERATURE OF 77°C (170°F) [BASE FUEL FLASH POINT OF 63°C (145°F)]

The above-mentioned decreases in fire resistance in the ballistic test, stemming from differences in base fuel flammability, was evidenced by near, but not complete, self-extinguishment in some tests. In such cases, only a small puddle continued to flame. In fact, the difference between complete self-extinguishment and this partial self-extinguishment is slight when compared with the overwhelming holocaust resulting when the neat base fuel is tested.

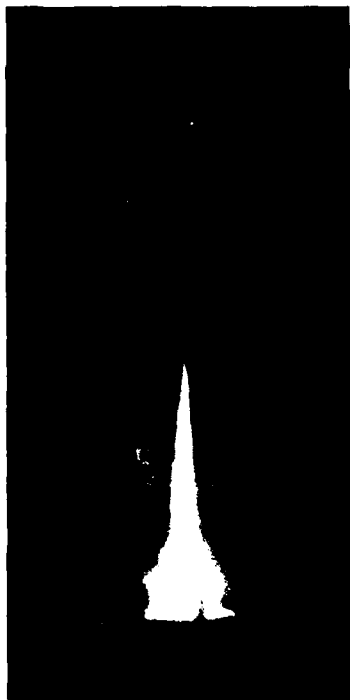
Overall, the results of these tests show that even though total extinguishment may not occur in every case when the referee-grade base fuel is used, the small amount of residual burning could easily be extinguished even under the severe conditions of the 77°C test temperature. Moreover, only in the case of the more flammable referee-grade base fuel did self-extinguishment not occur in every test of FRF-A or B.

3. Full-Scale Ballistic Tests

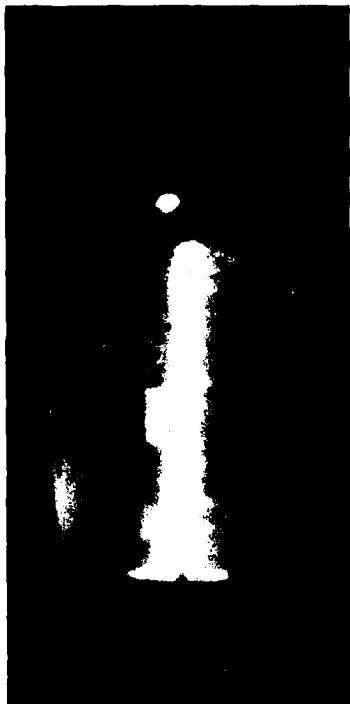
A series of five ballistic tests was conducted jointly by the U.S. Army Ballistic Research Laboratory (BRL), the authors, and a BRL contractor⁽¹⁷⁾ to evaluate the fire-resistant fuel formulations produced by SwRI. This series was intended to compare a full-scale ammunition threat with the results previously obtained at SwRI. The ballistic tests were conducted against a M113A armored personnel carrier using 3.2-inch, precision shaped charges. The fuel tank contained approximately 277 liters of fuel (MIL-F-46162A(MR), Grade II) (AFLRL Code No. 7225) with a flash point of 63°C heated to 77°C. Figure 29, which was reconstructed from high-speed 16 mm motion picture sequences, demonstrates the extreme incendiary effects created within the vehicle by the shaped charge.

The test sequence and results are described below.

- Test 1 - Neat referee-grade fuel: Large fireball upon impact followed by sustained burning. Assistance of firetruck was required to extinguish fire on floor inside of vehicle. Figure 30 illustrates the latter stages of the extinguishing effort.



Partial Penetration of Compartment



Full Passage Through Compartment



1.4 x 10⁻³ Seconds After Compartment Penetration



400 x 10⁻³ Seconds After Compartment Penetration

FIGURE 29. INTERIOR EFFECTS OF 3.2-INCH PRECISION SHAPED CHARGE ENTERING
M113A APC THROUGH FUEL TANK CONTAINING NEAT DIESEL FUEL AT
77°C AND PASSING THROUGH PERSONNEL COMPARTMENT



FIGURE 30. PHOTOGRAPH OF M113A ARMORED PERSONNEL CARRIER
NEAT FUEL FIRE BEING EXTINGUISHED FOLLOWING PENETRATION OF
FUEL TANK BY 3.2-INCH PRECISION SHAPED CHARGE

- Test 2 - Blend of 5% H_2O , 2% modified surfactant, and 0.2% AM-1: A greatly reduced fireball compared to Test No. 1. A small area of sustained burning occurred when a small amount of burning fuel, approximately 100 ml, became trapped in an area of vehicle isolated from the main fuel pool. This flame was extinguished by applying one "handful" of dirt.
- Test 3 - Blend of 10% H_2O and 2% modified surfactant: Large fireball (equal or slightly smaller than in Test No. 1) and no residual burning.
- Test 4 - Homogenized blend of 5% H_2O , 2% macroemulsion surfactant, and 0.2% AM-1: Reduced fireball and no residual burning. This test, a duplicate of Test No. 2 except for the different surfactant, was also a duplicate of blends previously evaluated by SwRI ballistic tests and impact dispersion tests during preliminary feasibility studies.

- Test 5 - Blend of 5% H₂O and 2% modified surfactant: Large fireball similar to that of Test No. 1; however, no residual burning.

With the exception of Test No. 5, the overall results of the full-scale ballistic tests with the M113 APC correlated exactly with results that had been obtained earlier with the 20-mm HEIT ballistic tests and the impact dispersion tests. These tests have shown that 0.2 percent undegraded antimist agent and 5 percent water are adequate to reduce the fireball and eliminate residual burning. They also have shown that 10 percent water alone is entirely adequate to eliminate residual burning. The 5-percent water blend was self-extinguishing in full-scale test No. 5 and is not self-extinguishing in the impact dispersion test.

G. Summary of Characteristics of FRF-A and FRF-B

When FRF-B is recycled back to the fuel tank from the fuel injector system of a diesel engine, much of the antimisting quality is destroyed by mechanically-induced depolymerization of the long-chain polymer molecules of the antimist agent.

In such cases, if the fueling and recycle rates were to be constant, and if all of the antimist agent in the recycled fuel were to be destroyed by the recycling process, the antimist agent content of the fuel mixture in the fuel tank would decrease according to the following relationship:

$$x/x_0 = (G/G_0)^{(R/F)}$$

where

x/x_0 = fraction of original antimist agent concentration in the fuel mixture

G/G_0 = fraction of the original fuel quantity remaining in the fuel tank

R/F = ratio of constant fuel recycle rate to constant fuel consumption rate.

In many Army ground vehicles, this recycle ratio is larger than unity. In such cases, the foregoing relationship indicates that the effective antimist agent content of the fuel tank could decrease more rapidly than the quantity of fuel in the tank. In any case involving fuel recycle, the relation shows

that the concentration of antimist agent in the fuel approaches zero as the fuel tank becomes empty. The previously discussed experimental flammability data presented in Table 23 tend to confirm that the flammability resistance of FRF-B in a fuel tank receiving recycled fuel may become equivalent to, or even poorer*, than that of FRF-A before all of the fuel has been consumed. The same data suggest that the flammability resistance of FRF-A will not change when subjected to the same fuel recycling conditions.

When other characteristics of FRF-A and FRF-B are considered, several additional deficiencies become apparent, and these are highlighted for both candidates by the underlined entries in Table 26. These tabulated comparative characteristics are based on data generated during the present FRF development program and information and data produced in this and other laboratories during previous antimist fuel research programs. However, this is not meant to imply that all fuel systems or antimist agents would incur the same debits as those observed in these investigations.

VI. CONCLUSIONS AND RECOMMENDATIONS

Various means have been investigated for producing fire-resistant fuels for Army combat vehicles by altering fuel compositions. Laboratory studies have yielded clear-to-hazy fire-resistant fuel microemulsions of water in surfactant-stabilized diesel fuel, without and with an antimist agent, FRF-A and FRF-B, respectively. The surfactant is a mixture of reaction products of diethanolamine and oleic acid. Flammability and ballistic tests reveal diminished mist flammability with self-extinguishing pool fires, even at temperatures above the base fuel flash point. No difficulties have been encountered in starting, idling, and running unmodified** diesel engines on such fuels under typical operating conditions.

The foregoing discussion has described the physical, flammability, and engine performance characteristics of the two candidate fire-resistant fuels, FRF-A

* If all antimist agent is destroyed, the lower water content of FRF-B could yield lower fire resistance than that of FRF-A.

** Removal of the primary, sock-type, filter was required with FRF-B.

TABLE 26. SUMMARY OF CHARACTERISTICS OF FRF-A AND FRF-B

Characteristic	FRF-A	FRF-B
<u>Flammability/Vulnerability</u>		
• Autoignition Temperature	• Substantially greater than that of neat fuel	• Substantially greater than that of neat fuel
• Flash Point	• Similar to that of neat fuel	• Similar to that of neat fuel
• Fire Point	• Greater than that of neat fuel	• Greater than that of neat fuel
• Pool Ignitability	• No flame propagation	• <u>Flame propagates</u>
• Mist Flammability		
Virgin Blend	• <u>Slightly less than that of neat fuel</u>	• Nil
Recycled From Diesel Engine	• <u>Slightly less than that of neat fuel</u>	• <u>Slightly less than that of neat fuel</u>
• Incendiary Ballistic Vulnerability		
Transient Fireball	• <u>Slightly smaller than that of neat fuel</u>	• Much smaller than that of neat fuel
Post-Impact Pool Fire	• Self-extinguishing	• Nil

TABLE 26. SUMMARY OF CHARACTERISTICS OF FRF-A AND FRF-B (Cont'd)

<u>FRF Preparation</u>	
• Blending and Storage Facility Requirements	• Simple mixer and tanks for base fuel, emulsifier, and water
• FRF Quality Assurance	• Visual Test
<u>Storage and Handling Characteristics</u>	
• Shear Stability	• No shear degradation
• Filterability	• No filterability problems
• Filter/Coalescer Effects	• Negligible coalescence
• Foaming Tendencies	• <u>Greater than base fuel</u>
• Phase Storage Stability	• Stable over 30 days
• Temperature Tolerance	• Stable between 3°C and 55°C (Six temp. cyclings)
• Water Dilution Effects	• Tolerates at least an additional 1%
• Fuel Dilution Effects	• Nil
	• Nil
	• Additional tank for AM-1 and provision for slower mixing (Takes 4 to 6 times longer in batch mixing)
	• Visual and additional test(s)
	• Degradation of AM-1 by pumping
	• Back pressure penalties and unwanted degradation of AM-1
	• Negligible coalescence
	• Similar to base fuel
	• Stable over 30 days
	• Stable between 3°C and 55°C (Six Temp. cyclings)
	• Tolerates at least an additional 0.5%
	• Nil

TABLE 26. SUMMARY OF CHARACTERISTICS OF FRF-A AND FRF-B (Cont'd)

<u>Utilization</u>	
• Physical Properties	
Viscosity at 40°C	<ul style="list-style-type: none"> • Slightly greater than that of neat fuel • Substantially greater than that of neat fuel
Pour Point	<ul style="list-style-type: none"> • About same as that of neat fuel • About same as that of neat fuel
Net Heat of Combustion	<ul style="list-style-type: none"> • 13% lower than that of neat fuel • 6% lower than that of neat fuel
• Engine Performance	
Fuel Recycle Effects	<ul style="list-style-type: none"> • Not detrimental • Unwanted AM-1 degradation
Filter Effects	<ul style="list-style-type: none"> • Same as for neat fuel • Vapor lock when filter in pump suction line and filter bypassing may occur elsewhere
Diesel Injector Effects	<ul style="list-style-type: none"> • Density-origin spray pattern changes • Density and viscosity-origin spray pattern changes
Diesel Exhaust Effects	<ul style="list-style-type: none"> • Increased unburned hydrocarbons • Increased carbon monoxide • Increased unburned hydrocarbons • Increased carbon monoxide • No change or increase in carbon monoxide • No change or decrease in nitrogen oxides • No change or decrease in particulates and smoke
Gas Turbine Nozzle Effects	<ul style="list-style-type: none"> • About same as with neat fuel • Predegradation of AM-1 required
Gas Turbine Exhaust Effects	<ul style="list-style-type: none"> • Decrease or no change in smoke • Increased smoke

and FRF-B. Since the Army intends to field FRF by the mid-1980's, a decision as to whether to proceed with FRF-A or with FRF-B advanced development for use in existing engines and vehicle fuel systems is required.

Plans for future FRF research and development by MERADCOM include basic research and advanced development, and applied research is being continued.

Research on future-generation FRF formulations should involve other considerations such as possible redesign of diesel engine and vehicle fuel systems to minimize FRF-B degradation during use and to optimize diesel engine parameters for FRF. Future-generation FRF research should also address aircraft turbine applications. Additionally, study of alternative means for reducing mist and bulk liquid flammability should be continued.

It is possible that this development of fire-resistant diesel fuel represents far more than achievement of objectives of this research program. It could well be the first step in a continuing military fuel formulation technology wherein diesel and other fuels would be designed within fire-hazard constraints as well as within usual environmental and engine performance limits.

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APPENDIX A

JFTOT THERMAL OXIDATION STABILITY TESTS

JFTOT THERMAL OXIDATION STABILITY TESTS

The influence of unmodified surfactant on the thermal oxidation stability of referee-grade base fuel was briefly investigated. Results presented in Table A-1 and Figure A-1 indicate that no serious instability problems should arise from the presence of surfactant.

TABLE A-1
JFTOT THERMAL OXIDATION STABILITY EVALUATIONS OF MIL-L-46162A(MR), GRADE II
REFEREE-GRADE BASE FUEL AND SURFACTANT-CONTAINING BASE FUEL

Sample Code No.	Tube Temp., °C	Visual	TDR Spun*	TDR Spot*	Filter ΔP, mm Hg
7225	246	2	7(4)	7.5(5)	0
7225	260	1**	1(0)	1(0)	0
7225	274	2	9.5(8)	12(9)	0
7225	280	3	11.5(10)	13(13)	0
7225	288	4	28(26)	29(27)	0
7225 + 3% unmodified surfactant	288	4	42(36)	44(42)	25 @ 10 min
7225 + 6% unmodified surfactant	288	4	38(35)	44(41)	25 @ 10 min

* Numbers in parentheses are replicate ratings of the same tubes
by a different observer.

** Bluish Color

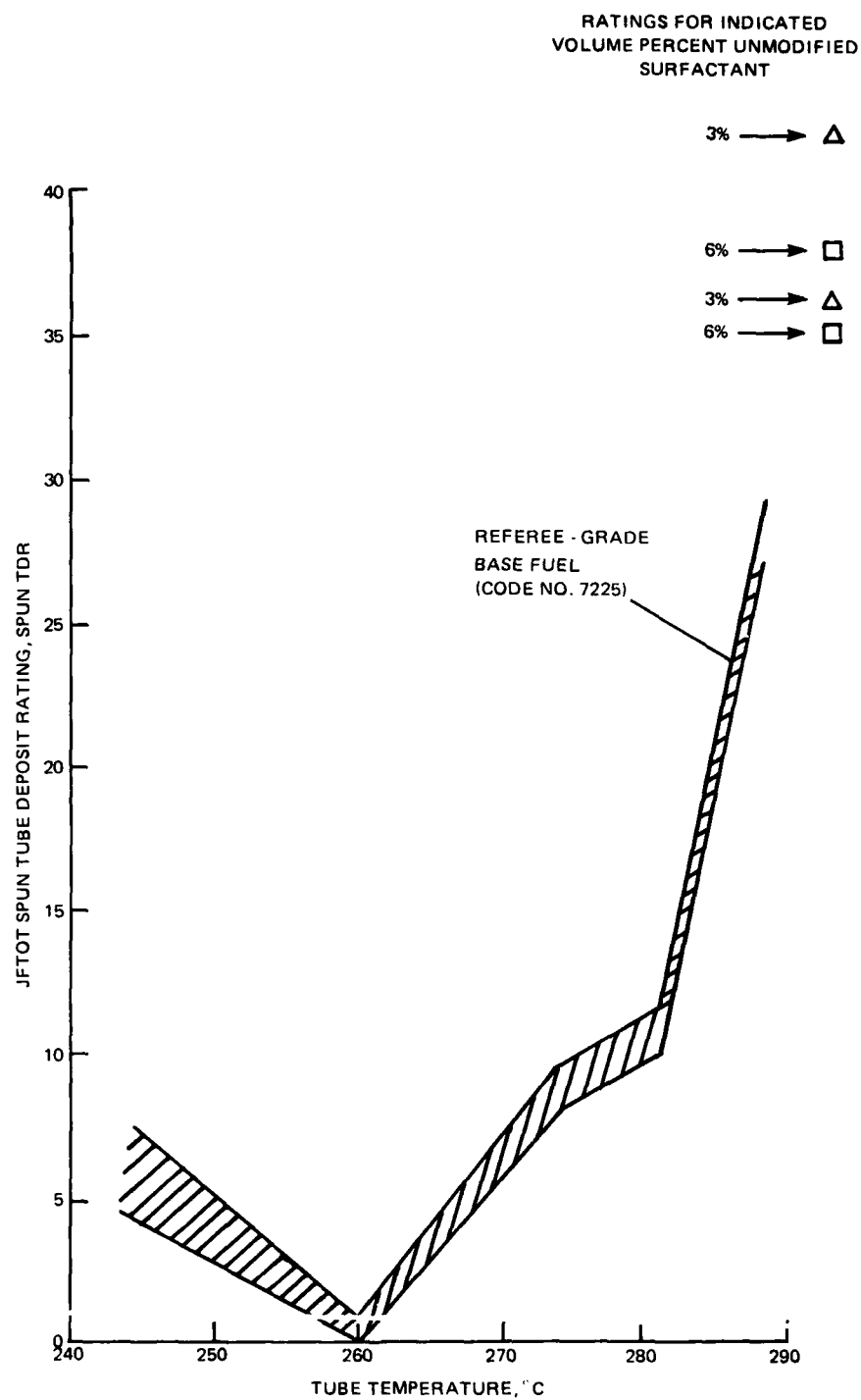


FIGURE A-1. ASTM D 3241 THERMAL OXIDATION STABILITY TEST RESULTS
FOR MIL-F-46162A(MR), GRADE II BASE FUEL
WITH AND WITHOUT ADDED SURFACTANT

APPENDIX B

EFFECT OF FIRE-RESISTANT FUEL ON ELASTOMERS

(Excerpted from report to W.R. Williams, Energy and Water Resources Lab, by P. Touchet, Material Technology Lab, U.S. Army Mobility Equipment Research and Development Command, 13 August 1979.)

TABLE B-1. COMPARISON OF FIRE-RESISTANT AND BASE DIESEL FUELS ON ELASTOMERS

	Urethanes		Low	Med	NBR/ PVC	Neoprene	ECO	Poly- Sulfide	Poly- Acrylate
	Ester 41802	Ether 41806	NBR J-231	NBR J-234	J-236	J-230	J-229	J-232	J-233
Tested in Base Fuel (DF-2)									
After 7 Days at 160°F									
Tensile Retained, %	85.0	60.0	39.0	42.0	65.0	34.0	76.0	85.0	39.0
200% Modulus Ret., %	87.5	83.0	---	64.0	77.0	---	88.0	---	---
Elongation Retained, %	105.0	105.0	111.0	78.0	123.0	58.0	81.0	109.0	64.0
Volume Swell, %	8.5	37.0	47.0	33.0	31.0	68.0	17.0	3.2	31.0
After 7 Days at Room Temp.									
Tensile Retained, %	103.0	48.0	55.0	53.0	74.0	31.0	66.0	80.0	42.0
200% Modulus Ret., %	94.5	76.0	---	65.0	90.0	---	73.0	---	---
Elongation Retained, %	111.0	103.0	109.0	94.0	137.0	51.0	81.0	112.0	87.0
Volume Swell, %	3.6	31.0	36.0	24.0	15.0	63.0	14.0	4.5	20.0
Tested in Fire-Resistant Diesel, FRF-197									
After 7 Days at 160°F									
Tensile Retained, %	1.5	18.0	43.0	46.0	49.0	22.0	47.0	65.0	22.0
200% Modulus Ret., %	---	37.0	---	75.0	---	---	76.0	---	---
Elongation Retained, %	8.3	208.0	89.0	77.0	91.0	39.0	58.0	88.5	45.0
Volume Swell, %	3.6	45.0	62.0	41.5	40.0	93.0	60.0	24.0	66.5
After 7 Days at Room Temp.									
Tensile Retained, %	54.0	39.0	46.0	52.0	69.0	20.0	67.0	84.0	40.0
200% Modulus Ret., %	58.0	60.0	---	84.0	64.0	---	87.0	---	---
Elongation Retained, %	107.0	109.0	56.0	74.0	124.0	34.0	75.0	95.0	59.0
Volume Swell, %	6.7	32.5	42.8	25.0	22.0	70.0	25.0	5.3	30.0

TABLE B-2. EFFECT OF FIRE-RESISTANT DIESEL FUEL ON ELASTOMERS

	Urethanes	
	<u>Ester</u> <u>41082</u>	<u>Ether</u> <u>41806</u>
After 14 Days at Room Temp		
Tensile Ret., %	49.0	33.0
200% Modulus Ret., %	58.0	54.0
Elongation Ret., %	103.0	101.0
Volume Swell, %	6.8	33.0
After 28 Days at Room Temp.		
Tensile Ret., %	49.0	36.0
200% Modulus Ret., %	56.0	55.0
Elongation Ret., %	111.0	113.0
Volume Swell, %	8.6	35.0
After 42 Days at Room Temp		
Tensile Ret., %	28.0	36.0
200% Modulus Ret., %	53.0	54.0
Elongation Ret., %	95.0	109.0
Volume Swell, %	10.0	35.0
After 14 Days at 160°F		
Tensile Ret., %	(1)	8.0
200% Modulus Ret., %	(1)	---
Elongation Ret., %	(1)	24.0
Volume Swell, %	(1)	47.0

NOTE: (1) Sample did not have enough integrity to be tested.

APPENDIX C

MICROBIOLOGICAL EVALUATION OF FIRE-RESISTANT FUEL

(Derived and excerpted from Memorandum Report 78-7-12, by
M.R. Rogers, DRDNA-YEP, NARADCOM, 9 July 1979)

AD-A083 610

SOUTHWEST RESEARCH INST SAN ANTONIO TX ARMY FUELS AN--ETC F/G 21/4
DEVELOPMENT OF ARMY FIRE-RESISTANT DIESEL FUEL.(U)

DEC 79 W D WEATHERFORD, G E FODOR

DAAK70-78-C-0001

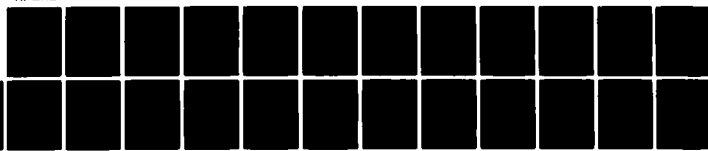
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A. Materials

1. Deionized water and 300 ppm TDS tap water.
2. Referee-grade base diesel fuel.
3. Modified surfactant, unmodified surfactant, and modified surfactant from an alternate supplier.
4. FRF-A formulated with deionized water and tap water, referee-grade diesel fuel, and unmodified and modified surfactants from two suppliers.
5. FRF-B (sans AM-1) formulated with deionized water, referee-grade diesel fuel, and unmodified surfactant.

B. Test Organisms

1. Pseudomonas (only with item A5 and with item A4 made with deionized water and unmodified surfactant)
2. Cladosporium resinae.
3. ASTM mixed fungal spore inoculum (only with item A5 and with item A4 made with deionized water and unmodified surfactant).

C. Test Variables

1. Static vs. shaking incubation.
2. Samples cultured with and without Bushnell Haas medium.
3. Autoclaved vs. nonautoclaved.
4. Pseudomonas inoculated samples incubated at 37°C and the fungal spore inoculated samples incubated at 30°C.

D. Conclusions

Based on this limited series of experiments using the specified test organisms, all of the surfactants possess excellent biostatic properties. Fire-resistant fuel formulated with these emulsifying agents also failed to support the growth of the test microorganisms used in these tests. Although the tests carried out in this study were basically screening tests against a limited number of microorganisms, the micro-organisms selected were those which most frequently are found in a contaminated fuel system. If these emulsifying agents are used for other end items uses such as in plasticizers, additional microbial testing is probably indicated to ascertain their dual role as a plasticizer and antimicrobial agent, and in order to develop a broader antimicrobial spectra for these compounds.

APPENDIX D

250-HOUR ENDURANCE TEST IN CUE-1790

Test No.: 1 Base Fuel Case

Fuel: Referee-Grade DF-2 [(MIL-F-46162A(MR),
Grade II] (Code No. 7225)

Lubricant: MIL-L-2104C, Grade 30
(Code No. 6856)

Date Started: 23 May 1978

Date Completed: 16 June 1978

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TABLE D-1. OPERATING SUMMARY

Test No.: 1
Fuel Code: 7225

Date Completed: 16 June 1978
Lubricant Code: 6856

<u>Variable</u>	<u>Average</u>	<u>Minimum</u>	<u>Maximum</u>
Speed, rpm	1805		
Load, N-m (lb-ft)	176(130)	1798	1814
Obs. Power, kW (Bhp)	33.3(44.7)	172(127)	180(133)
Ind. Power, kW (Ihp)	42.0(56.4)	32.4(43.5)	34.0(45.6)
Fuel Rate, kg/hr (lb/hr)	8.48(18.7)	41.1(55.2)	42.7(57.2)
Specific Fuel Consumption, kg/Kw-hr (lb/Bhp-hr)	0.254(0.418)	8.35(18.4)	8.57(18.9)
Temperature, °C(°F)		0.252(0.414)	0.257(0.423)
Exhaust			
Air Intake	543(1010)	538(1000)	554(1030)
Cylinder Head	87(188)	86(187)	87(189)
Cylinder Head at Nozzle	104(219)	99(210)	112(233)
Cylinder Liner	137(279)	130(266)	143(290)
Front Exhaust	137(278)	126(258)	143(290)
Oil to Engine	168(334)	160(320)	173(344)
Oil before Cooler	77(170)	71(160)	82(180)
Fuel In	91(195)	81(178)	94(202)
Balance Oil	52(125)	44(112)	57(135)
Cooling Air In	82(180)	64(148)	88(191)
	47(117)	40(104)	52(126)
Pressures, kPa			
Oil Gallery (psi)	345(50)	345(50)	345(50)
Piston Oil (psi)	172(25)	169(25)	172(25)
Fuel (psi)	107(15)	103(15)	107(15)
Cooling Air (in H ₂ O)	1.6(6.4)	1.5(6.0)	1.7(7.0)
Intake Boost (in Hg)	159(47.0)	156(46.2)	161(47.5)
Exhaust (in Hg)	130(38.4)	127(37.6)	133(39.4)

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TABLE D-2. PRETEST MEASUREMENTS

Test No.: 1
Fuel Code: 7225

Date: 18 May 1978
Lubricant Code: 6856

CYLINDER BORE MEASUREMENTS
Diameter, mm (inch)

Distance from Bottom of Liner, mm(in.)	Longitudinal	Transverse	Out of Round
57.2 (2.25)	146.119 (5.7527)	146.103 (5.7521)	0.015 (0.0006)
158.8 (6.25)	146.091 (5.7516)	146.088 (5.7515)	0.003 (0.0001)
209.6 (8.25)	146.080 (5.7512)	146.075 (5.7510)	0.005 (0.0002)
247.7 (9.75)	146.060 (5.7504)	146.055 (5.7502)	0.005 (0.0002)
266.7 (10.50)	146.027 (5.7491)	146.025 (5.7490)	0.003 (0.0001)

PISTON SKIRT MEASUREMENTS

1.27 mm (0.5 in.) from Bottom: 146.834mm (5.7415 in.)
25.4 mm (1.0 in.) from Top: 145.750mm (5.7382 in.)

PISTON RING MEASUREMENTS, mm (in.)

	End Gap	Side Clearance
Top Ring	1.19 (0.047)	---
Second Ring	0.81 (0.32)	0.15 (0.006)
Third Ring	0.74 (0.029)	0.13 (0.005)
Oil Control Ring	0.76 (0.030)	0.05 (0.002)

Connecting Rod Bearing (Journal = 95.199 mm (3.7480 in.))

	Diameter	Clearance
Front	95.347 (3.7538)	0.147 (0.0058)
Rear	95.341 (3.7536)	0.142 (0.0056)
Average	95.344 (3.7537)	0.145 (0.0057)

Piston Pin Bushing = 54.051 mm (2.1280 in.)

	Diameter	Clearance
Front	53.983 (2.1253)	0.069 (0.0027)
Rear	53.985 (2.1254)	0.066 (0.0026)
Average	53.985 (2.1254)	0.068 (0.0027)

TABLE D-3. EXHAUST EMISSION MEASUREMENTS

Test No.: 1

Fuel Code: 7225

Lubricant Code: 6856

Test Hour	NO(ppm)	NO _x (ppm)	UBH(ppm carbon)	CO(%)	CO ₂ (%)	O ₂ (%)
2	660	700	161	0.17	9.75	7.4
118	673	690	108	0.26	10.4	6.3
230	650	665	260	0.17	9.22	8.0

TABLE D-4.
TEST 1
DF-2 In The CUE-1790 Engine
Endurance Test Engine Dimensions
Test Time: 250 Hours

Cylinder Liner ID, Millimeters (Inches)

	Longitudinal Millimeters (Inches) from Bottom of Liner				
	57(2.25)	159(6.25)	210(8.25)	248(9.75)	267(10.50)
Before	146.119(5.7527)	146.091(5.7516)	146.080(5.7512)	146.060(5.7504)	146.027(5.7491)
After	146.126(5.7530)	146.111(5.7524)	146.096(5.7518)	146.070(5.7508)	146.020(5.7488)
Change	0.007(0.0003)	0.020(0.0008)	0.016(0.0006)	0.010(0.0004)	-0.007(-0.0003)

	Transverse Millimeters (Inches) from Bottom of Liner				
	57(2.25)	159(6.25)	210(8.25)	248(9.75)	267(10.50)
Before	146.103(5.7521)	146.088(5.7515)	146.075(5.7510)	146.055(5.7502)	146.025(5.7490)
After	146.114(5.7525)	146.101(5.7520)	146.083(5.7513)	146.037(5.7495)	146.014(5.7486)
Change	0.011(0.0004)	0.013(0.0005)	0.008(0.0003)	-0.018(-0.0007)	-0.011(-0.0004)

Average Cylinder Liner ID Change: 0.000 mm (0.0000 in.)

Piston Skirt OD, Millimeters (Inches)

	13 mm(0.5 in.) from bottom	25 mm(1 in.) from top
Before	145.834(5.7415)	145.750(5.7382)
After	145.796(5.7400)	145.745(5.7380)
Change	-0.038(-0.0015)	-0.005(-0.0002)

Average Piston Skirt OD Change: -0.023 mm (-0.0009 in.)

Piston Ring End Gap, Millimeters (Inches)

	Top	No. 2 Compression	No. 3 Compression	Oil
Before	1.19(0.047)	0.81(0.032)	0.74(0.029)	0.76(0.030)
After	1.22(0.048)	0.86(0.034)	0.79(0.031)	0.79(0.031)
Change	0.03(0.001)	0.05(0.002)	0.05(0.002)	0.03(0.001)

Average Piston Ring End Gap Change: 0.05 mm(0.002 in.)

CRC DIESEL RATING SYSTEM

STANDARD COMPUTATION SHEET FOR PISTON RATING

RATER E R Lyons DATE 6-20-78
LABORATORY TEST NUMBER 1790-1
STAND NO. 3 ENGINE NO. 1790
FUEL 7225

TEST LABORATORY 6856				LUBRICANT				FUEL 7225				ENGINE NO. 7225				STAND NO. 7225				NO. 1 GROOVE, VOLUME %				PISTON WTD* RATING				322.51					
DEPOSIT TYPE		DEPOSIT FACTOR		GROOVES												LANDS												UNDER-CROWN					
				NO. 1	NO. 2	NO. 3	NO. 4	NO. 1	NO. 2	NO. 3	NO. 4	NO. 1	NO. 2	NO. 3	NO. 4	NO. 1	NO. 2	NO. 3	NO. 4	NO. 1	NO. 2	NO. 3	NO. 4	NO. 1	NO. 2	NO. 3	NO. 4	NO. 1	NO. 2	NO. 3	NO. 4		
				AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT		
CARBON				100	100.0	100	100.0					20	20.00	80	80.00																		
MHC																																	
MC																																	
LC												80	20.00	10	2.50																		
VLC																																	
CARBON RATING				100.00		100.00						40.00		82.50																			
BL																																	
DBrL																																	
AL																																	
LAL																																	
VLAL																																	
RL														10	0.01																		
LACQUER RATING														0.01																			
CLEAN								100	0	100	0							100	0	100	0												
ZONAL RATING																																	
LOCATION FACTOR																																	
WEIGHTED RATING				100.0		100.0		0	0	0			40.00		82.51		0	0	0	0											0	0	0

WEIGHTED TOTAL DEPOSITS

FIGURE D-1.
CUE-1790 TEST NO. 1
Fuel Code: 7225 Oil Code: 6856

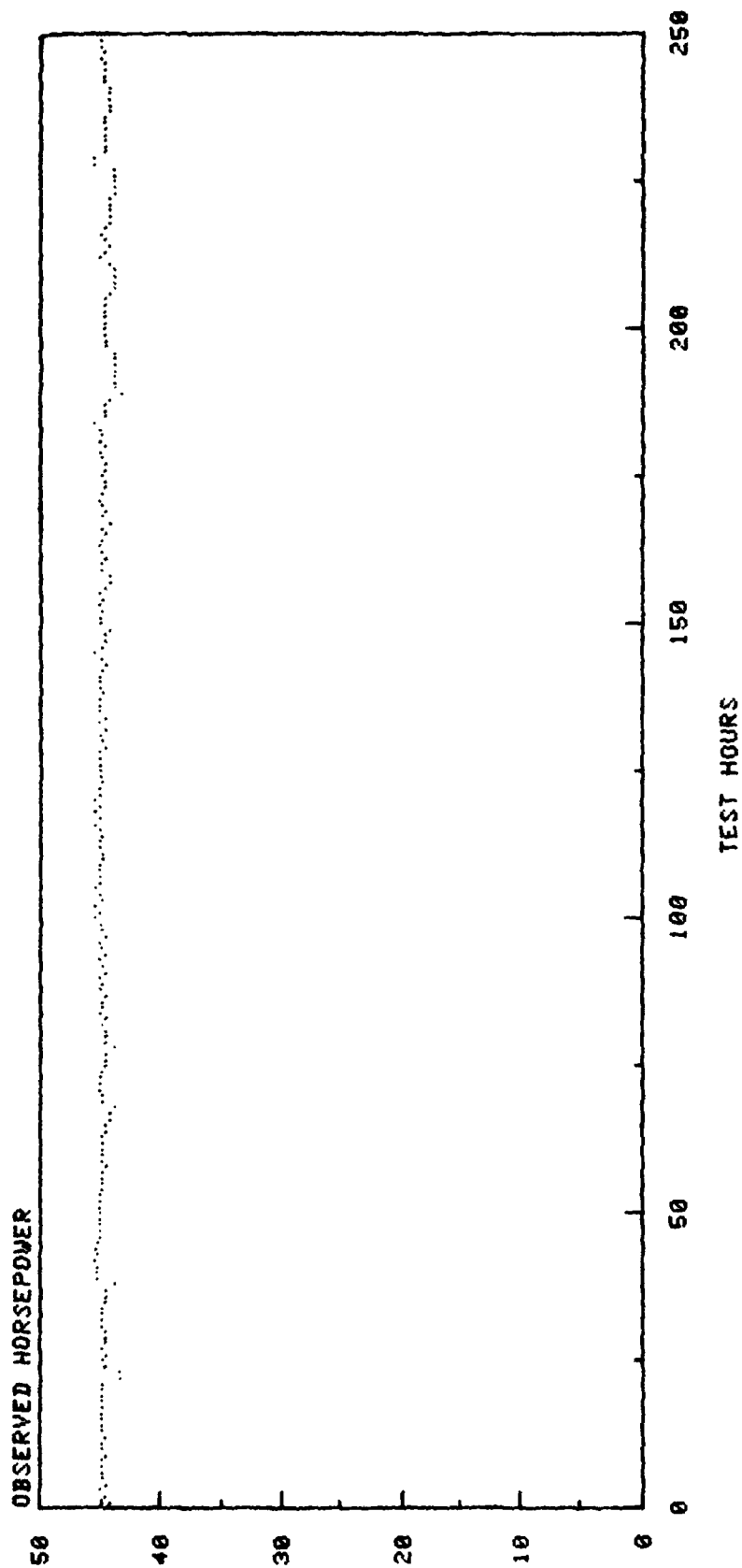
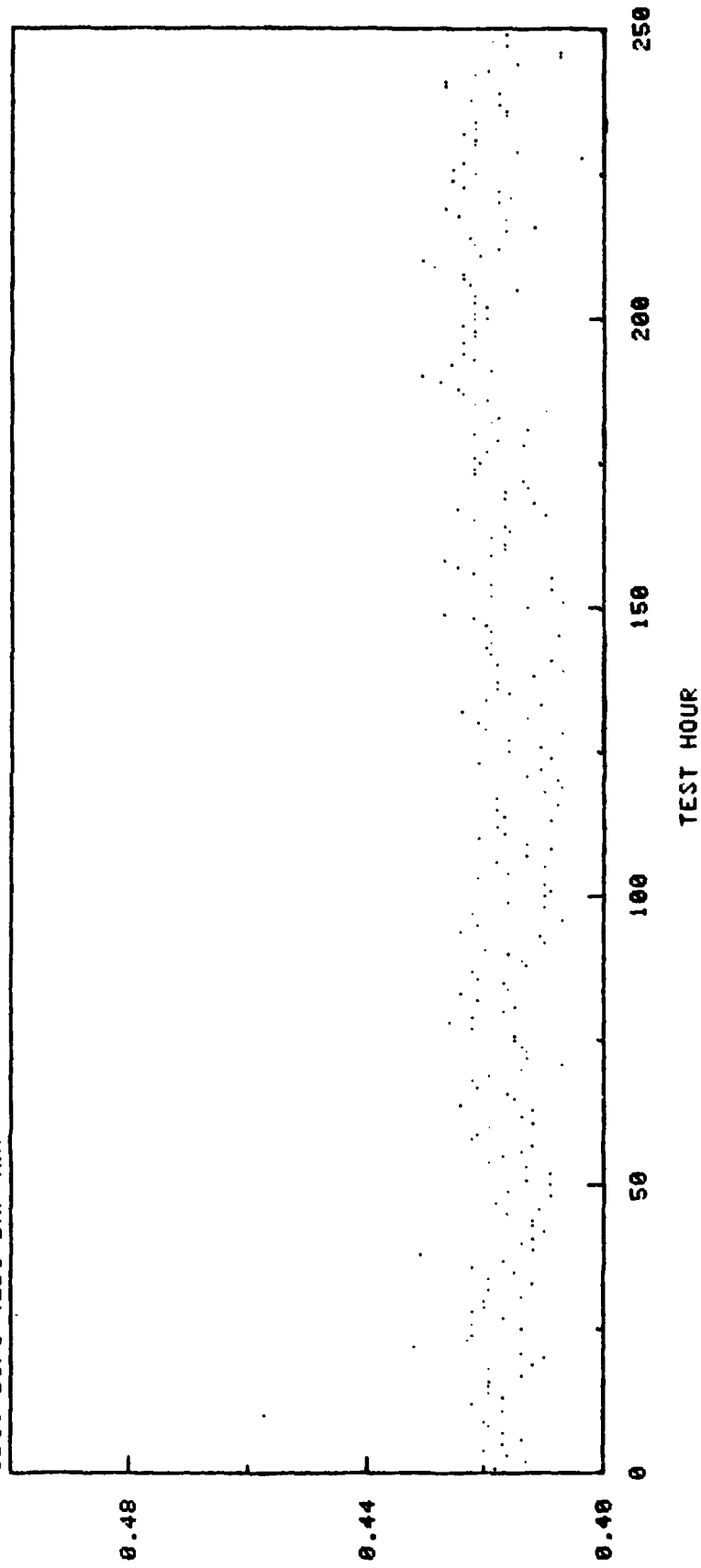


FIGURE D-2.
CUE-1790 TEST NO. 1
Fuel Code: 7225 Oil Code: 6856

OBS. BSFC (LBS/BHP-HR)



Date: 20 June 1978
Fuel Code: 7225

Test No. 1790-1

Technician: Ed Lyons
Lubricant Code: 6856

POST TEST DESCRIPTION OF ENGINE

Rings: All are free, no ringface burn. No sign of distress. Oil control ring slots all open.

Piston: Some light scratches on skirt, lands are normal. Some ring supporting carbon in first two grooves.

Valves: Some carbon on intake valve face and corresponding pits in seat. Exhaust looks normal. Tulip deposit on intake is 1.0; Exhaust is 0.25 Demerit Rating.

Cylinder: Normal light scratches and 100% light lacquer.

Conrod Bearing looks good. The top has a little more "shine" from taking the power. "Shine" is probably bright metal due to close contact to journal.

APPENDIX E

250-HOUR ENDURANCE TEST IN CUE-1790

Test No.: 2

Fuel: FRF-A (10% deionized water,
6% modified surfactant, 84%
referee-grade DF-2)

Lubricant: MIL-L-2104C, Grade 30
(Code No. 6856)

Date Started: 14 July 1978

Date Completed: 28 August 1978

TABLE E-1. OPERATING SUMMARY

Test No.: 2
 Fuel: FRF-A (deionized water)

Date Completed: 28 August 1978
 Lubricant Code: 6856

Variable	Average	Minimum	Maximum
Speed, rpm	1803	1797	1810
Load, N-m (lb-ft)	174(128)	172(127)	175(129)
Obs. Power, kW (Bhp)	32.8(43.9)	32.4(43.5)	33.0(44.2)
Ind. Power, kW (Ihp)	42.5(57.0)	42.2(56.6)	42.7(57.2)
Fuel Rate, kg/hr (lb/hr)	9.48(20.9)	8.89(19.6)	10.34(22.8)
Specific Fuel Consumption, kg/kW-hr (lb/Bhp-hr)	0.290(0.476)	0.274(0.451)	0.314(0.516)
Temperature, °C(°F)			
Exhaust	554(1029)	516(960)	582(1080)
Air Intake	87(188)	86(187)	87(189)
Cylinder Head	131(267)	123(254)	141(285)
Cylinder Head at Nozzle	138(281)	129(264)	144(292)
Cylinder Liner	112(234)	108(226)	119(247)
Front Exhaust	156(313)	143(290)	165(329)
Oil to Engine	76(168)	72(162)	81(178)
Oil before Cooler	88(190)	83(182)	94(202)
Fuel In	53(127)	43(110)	54(130)
Balance Oil	78(173)	59(138)	82(180)
Cooling Air In	45(113)	41(106)	48(118)
Pressures, kPa			
Oil Gallery (psi)	345(50)	345(50)	345(50)
Piston Oil Jet (psi)	179(26)	179(26)	179(26)
Fuel (psi)	103(15)	86(12.5)	114(16.5)
Cooling Air (in. H ₂ O)	1.5(6.0)	1.5(6.0)	1.5(6.0)
Intake Boost (in. Hg)	159(47.0)	158(46.5)	161(47.5)
Exhaust (in. Hg)	132(38.9)	125(36.9)	134(39.5)

TABLE E-2. PRETEST MEASUREMENTS

Test No.: 2
 Fuel: FRF-A (deionized water)

Date: 14 July 1978
 Lubricant Code: 6856

CYLINDER BORE MEASUREMENTS
 Diameter, mm (inch)

Distance from Bottom of Liner, mm(in.)	Longitudinal	Transverse	Out of Round
57.2 (2.25)	146.103(5.7521)	146.096(5.7518)	0.008(0.0003)
158.8 (6.25)	146.098(5.7519)	146.093(5.7517)	0.005(0.0002)
209.6 (8.25)	146.108(5.7523)	146.096(5.7518)	0.013(0.0005)
247.7 (9.75)	146.103(5.7521)	146.083(5.7513)	0.020(0.0008)
266.7 (10.50)	146.083(5.7513)	146.075(5.7510)	0.008(0.0003)

PISTON SKIRT MEASUREMENTS

1.27 mm (0.5 in) from Bottom: 145.816 mm (5.7408 in.)
 25.4 mm (1.0 in) from Top: 145.745 mm (5.7380 in.)

PISTON RING MEASUREMENTS, mm (inch)

	End Gap	Side Clearance
Top Ring	1.17(0.046)	---
Second Ring	0.76(0.030)	0.15(0.006)
Third Ring	0.81(0.032)	0.13(0.005)
Oil Control Ring	0.69(0.027)	0.05(0.002)

Connecting Rod Bearing (Journal = 95.199 mm (3.7480 in.)

	Diameter	Clearance
Front	95.334(3.7533)	0.135(0.0053)
Rear	95.339(3.7535)	0.140(0.0055)
Average	95.336(3.7534)	0.137(0.0054)

Piston Pin Bushing = 54.077 mm (2.1290 in.)

	Diameter	Clearance
Front	53.975(2.1250)	0.102(0.0040)
Rear	53.975(2.1250)	0.102(0.0040)
Average	53.975(2.1250)	0.102(0.0040)

TABLE E-3. EXHAUST EMISSION MEASUREMENTS

Test No.: 2

Fuel: FRF-A

Lubricant Code: 6856

Test Hour	Fuel	NO(ppm)	NO _x (ppm)	UBH(ppm carbon)	CO(%)	CO ₂ (%)	O ₂ (%)
1	7725	565	578	102	0.28	9.63	7.5
1	FRF	545	555	198	0.14	9.25	8.15
139	7725	605	610	142	0.39	11.75	4.4
139	FRF	566	569	371	0.30	10.6	6.1
250	7225	672	680	62	0.40	10.85	5.5
250	FRF	630	650	161	0.28	10.2	6.65
250	7725*	643	652	148	0.34	10.0	6.7

* All emissions measurements were made at equal fuel rate settings except for point noted, where the rack setting was decreased to produce power with fuel 7725 equal to that of FRF-A.

TABLE E-4.
TEST 2
FRF-A In The CUE-1790 Engine
Endurance Test Engine Dimensions
Test Time: 250 Hours

Cylinder Liner ID, Millimeters (Inches)

	Longitudinal Millimeters (Inches) from Bottom of Liner				
	57(2.25)	159(6.25)	210(8.25)	248(9.75)	267(10.50)
Before	146.103(5.7521)	146.098(5.7519)	146.108(5.7523)	146.103(5.7521)	146.083(5.7513)
After	146.096(5.7518)	146.098(5.7519)	146.096(5.7518)	146.088(5.7515)	(*)
Change	-0.007(-0.0003)	0.000(0.0000)	-0.012(-0.0005)	-0.015(-0.0006)	(*)

	Transverse Millimeters (Inches) from Bottom of Liner				
	57(2.25)	159(6.25)	210(8.25)	248(9.75)	267(10.50)
Before	146.096(5.7518)	146.093(5.7517)	146.096(5.7518)	146.083(5.7513)	146.080(5.7510)
After	146.106(5.7522)	146.103(5.7521)	146.108(5.7523)	146.106(5.7522)	(*)
Change	0.010(0.0004)	0.010(0.0004)	0.012(0.0005)	0.023(0.0009)	(*)

Average Cylinder Liner ID Change: 0.003 mm (0.0001 in.)

Piston Skirt OD, Millimeters (Inches)

	13 mm(0.5 in.) from bottom	25 mm(1 in.) from top
Before	145.816(5.7408)	146.799(5.7401)
After	145.799(5.7401)	145.740(5.7378)
Change	-0.017(-0.0007)	-0.059(-0.0023)

Average Piston Skirt OD Change: -0.038 mm(-0.0015 in.)

Piston Ring End Gap, Millimeters (Inches)

	Top	No. 2 Compression	No. 3 Compression	Oil
Before	1.17(0.046)	0.76(0.030)	0.81(0.032)	0.69(0.027)
After	1.19(0.047)	0.79(0.031)	0.84(0.033)	0.76(0.030)
Change	0.03(0.001)	0.03(0.001)	0.03(0.001)	0.08(0.0003)

Average Piston Ring End Gap Change: 0.04mm(0.002in)

* Unable to measure due to carbon.

TABLE E-5

CRC DIESEL RATING SYSTEM**STANDARD COMPUTATION SHEET FOR PISTON RATING**RATER E R Lyons DATE 9-1-78LABORATORY TEST NUMBER 1790-2STAND NO. 3 ENGINE NO. 1790FUEL ERFA (deionized water)

TEST PROCEDURE _____

TEST HOURS _____

TEST LABORATORY _____

LUBRICANT 6856

NO. 1 GROOVE, VOLUME %	285.50
PISTON WTD* RATING	

DEPOSIT TYPE		DEPOSIT FACTOR	GROOVES								LANDS								UNDER-CROWN				
			NO. 1		NO. 2		NO. 3		NO. 4		NO. 1		NO. 2		NO. 3		NO. 4						
			AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT	AREA-%	DEMERIT			AREA-%	DEMERIT	
CARBON			HC	1.00	100	100.0	100	100.0					15	15.00	25	25.00							
			MHC	0.75																			
			MC	0.50								5	2.50	25	12.50								
			LC	0.25								80	20.00	43	10.75								
			VLC	0.15																			
			CARBON RATING		100.0		100.0					37.50		48.25									
LACQUER			BL	0.100																			
			DBrL	0.075																			
			AL	0.050																			
			LAL	0.025												2	0.050						
			V/LAL	0.010																			
			RL	0.001																			
			LACQUER RATING											0.050									
			CLEAN	0				100	0		100	0			5	0	0	0	0	100	0		
			ZONAL RATING [†]												0.050								
			LOCATION FACTOR																				
			WEIGHTED RATING		100.0		100.0		0		0		37.50		48.30		0		0		0	0	

*WEIGHTED TOTAL DEPOSITS

FIGURE E-1.
CUE-1790 TEST NO. 2
Fuel Code: 7225 Oil Code: 6856

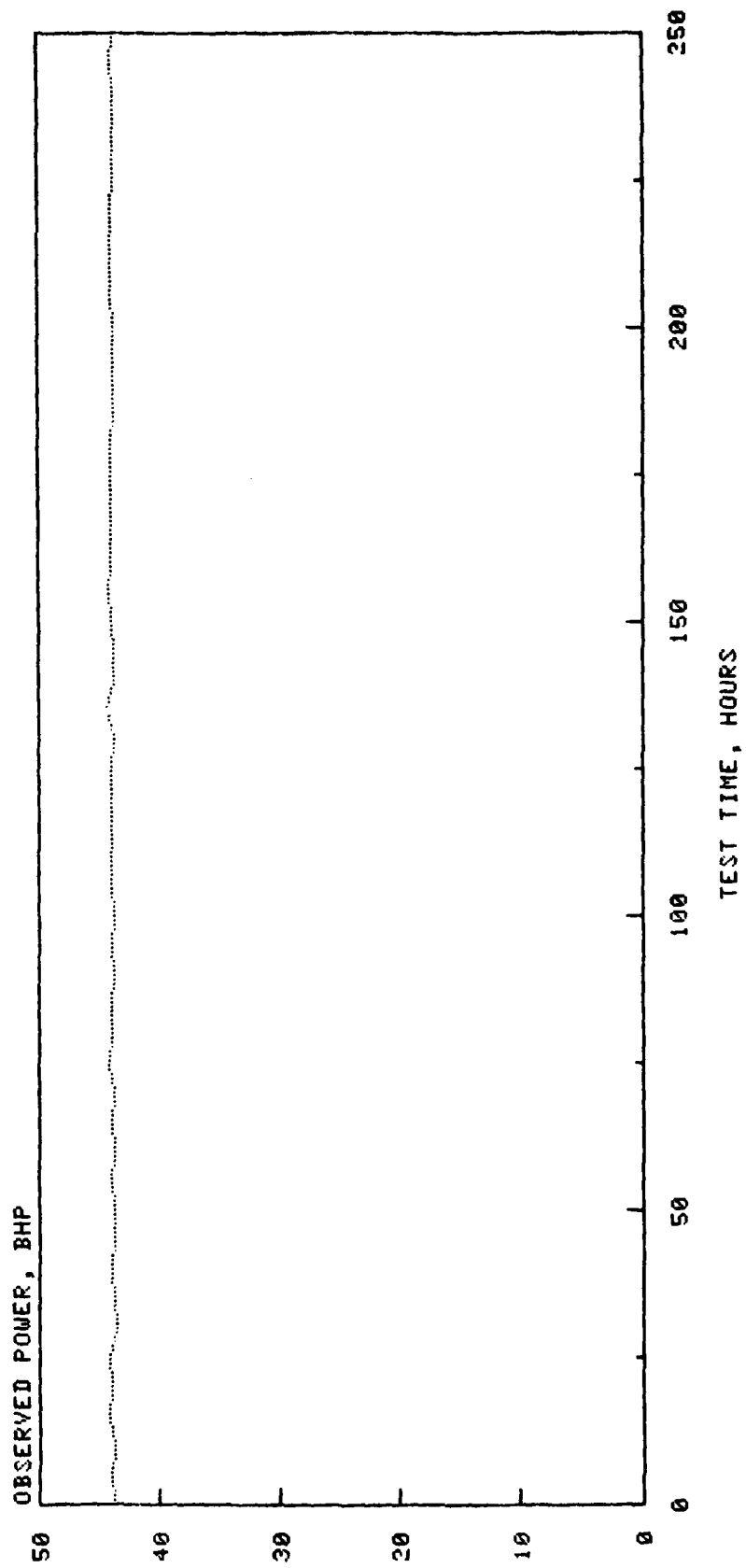
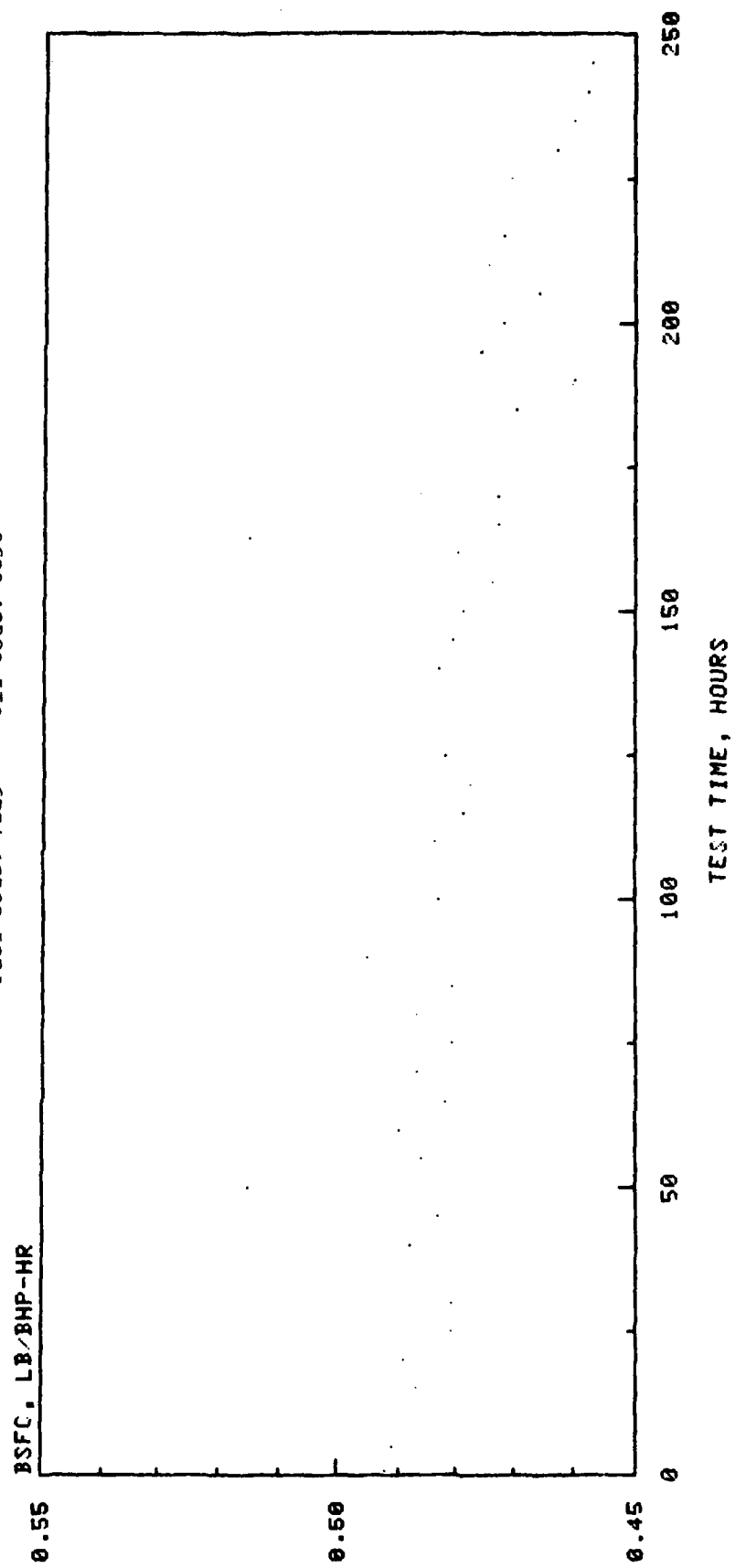


FIGURE E-2.
CUE-1790 TEST NO. 2
Fuel Code: 7225 Oil Code: 6856



Date: 1 September 1978 Test No. 1790-2 Technician: Ed Lyons
Fuel: FRF-A (deionized water) Lubricant Code: 6856

POST TEST DESCRIPTION OF ENGINE

Rings: All are free, no ring face burn. No sign of distress,
oil control ring slots all open.

Piston: Very light wear pattern lands normal.

Valves: No. 9 lacquer to No. 3 lacquer on intake valve face. 1.0
demerit rating of tulip, stem is normal. No. 9 lacquer on
face of exhaust valve 1.0 demerit rating of tulip, stem
normal. Both faces of valves and the seats are normal

Cylinder: Looks good, light wear and 100 percent light lacquer.

Conrod Bearing: Light wear pattern and some light scratches.

APPENDIX F

250-HOUR ENDURANCE TEST IN CUE-1790

Test No.: 3

Fuel: FRF-A (10% 300 ppm TDS tap water,
6% modified surfactant, and
84% referee-grade DF-2)

Lubricant: MIL-L-2104C, Grade 30 (Code No. 6856)

Date Started: 27 December 1978

Date Completed: 5 February 1979

TABLE F-1. OPERATING SUMMARY

Test No.: 3
 Fuel: FRF-A (tap water)

Date Completed: 5 February 1979
 Lubricant Code: 6856

Variable	Average	Minimum	Maximum
Speed, rpm	1802	1800	1814
Load, N-m (lb-ft)	184(136)	163(120)	194(143)
Obs. Power, kW (Bhp)	34.8(46.7)	30.7(41.1)	36.5(49.0)
Ind. Power, kW (Ihp)	40.4(54.2)	36.3(48.7)	42.2(56.6)
Fuel Rate, kg/hr (lb/hr)	9.75(21.5)	8.44(18.6)	10.02(22.1)
Specific Fuel Consumption, kg/kW-hr (lb/Bhp-hr)	0.280(0.460)	0.266(0.438)	0.291(0.478)
Temperature, °C(°F)			
Exhaust	514(958)	441(825)	543(1010)
Air Intake	87(188)	83(182)	89(192)
Cylinder Head	94(202)	84(184)	109(228)
Cylinder Head at Nozzle	126(259)	106(222)	135(275)
Cylinder Liner	101(214)	68(155)	113(236)
Front Exhaust	141(286)	110(230)	149(301)
Oil to Engine	77(171)	69(157)	82(180)
Oil before Cooler	86(187)	76(168)	93(200)
Fuel In	44(111)	33(92)	49(120)
Balance Oil	73(163)	49(120)	81(177)
Cooling Air In	39(102)	27(80)	47(116)
Pressures, kPa			
Oil Gallery (psi)	352(51)	345(50)	365(53)
Piston Oil (psi)	172(25)	172(25)	179(26)
Fuel (psi)	110(16)	110(16)	110(16)
Cooling Air (in. H ₂ O)	1.5(6.0)	1.5(5.9)	1.5(6.0)
Intake Boost (in. Hg)	159(47.1)	157(46.4)	167(49.2)
Exhaust (in. Hg)	132(39.0)	122(36.1)	135(39.9)

TABLE F-2. PRETEST MEASUREMENTS

Test No.: 3
 Fuel: FRF-A (tap water)

Date: 3 October 1978
 Lubricant Code: 6856

CYLINDER BORE MEASUREMENTS

Diameter, mm (inch)

Distance from Bottom of Liner, mm(in.)	Longitudinal	Transverse	Out of Round
57.2 (2.25)	146.116(5.7526)	146.106(5.7522)	0.010(0.0004)
158.8 (6.25)	146.106(5.7522)	146.111(5.7524)	0.005(0.0002)
209.6 (8.25)	146.106(5.7522)	146.101(5.7520)	0.005(0.0002)
247.7 (9.75)	146.083(5.7513)	146.083(5.7513)	0.000(0.0000)
266.7 (10.50)	146.050(5.7500)	146.050(5.7500)	0.000(0.0000)

PISTON SKIRT MEASUREMENTS

1.27 mm (0.5 in.) from Bottom: 145.847 mm (5.7420 in.)
 25.4 mm (1.0 in.) from Top: 145.796mm (5.7400 in.)

PISTON RING MEASUREMENTS, mm (inch)

	End Gap	Side Clearance
Top Ring	1.22(0.048)	---
Second Ring	0.81(0.032)	0.13(0.005)
Third Ring	0.76(0.030)	0.13(0.005)
Oil Control Ring	0.69(0.027)	0.05(0.002)

Connecting Rod Bearing (Journal = 95.199 mm (3.7480 in.))

	Diameter	Clearance
Front	95.354 (3.7541)	0.099(0.0039)
Rear	95.352 (3.7540)	0.102 (0.0040)
Average	95.353 (3.7541)	0.102 (0.0040)

Piston Pin Bushing = 54.089 mm (2.1295 in.)

	Diameter	Clearance
Front	53.975(2.1250)	0.114(0.0045)
Rear	53.975(2.1250)	0.114(0.0045)
Average	53.975(2.1250)	0.114(0.0045)

TABLE F-3. EXHAUST EMISSION MEASUREMENTS

Test No.: 3

Fuel: FRF-A (tap water)

Lubricant Code: 6856

Test Hour	Fuel	NO(ppm)	NO _x (ppm)	UBH(ppm carbon)	CO(%)	CO ₂ (%)	O ₂ (%)
1	7725 ⁽¹⁾	885	920	396	0.18	9.5	7.55
1	FRF	816	855	371	0.15	9.4	7.75
177	7725 ⁽²⁾	880	920	396	0.25	9.6	7.2
177	FRF	834	850	458	0.21	9.7	7.2
250	7225 ⁽¹⁾	820	930	ND	0.23	10.6	6.4
250	FRF	950	970	ND	0.16	10.0	7.0

1: Measurements conducted at equal load settings.

2: Measurements conducted at equal fuel rate (vol) settings.

ND: Not determined due to equipment malfunction.

TABLE F-4.
TEST 3
FRF-A in the CUE-1790 Engine
Endurance Test Engine Dimensions
Test Time: 250 Hours

Cylinder Liner ID, Millimeters (Inches)

	Longitudinal Millimeters (Inches) from Bottom of Liner				
	57(2.25)	159(6.25)	210(8.25)	248(9.75)	267(10.50)
Before	146.116(5.7526)	146.106(5.7522)	146.106(5.7522)	146.083(5.7513)	146.050(5.7500)
After	146.119(5.7527)	146.098(5.7519)	146.096(5.7518)	146.068(5.7507)	145.951(5.7461)
Change	0.003(0.0001)	-0.008(-0.0003)	-0.010(-0.0004)	-0.015(-0.0006)	-0.099(-0.0039)

	Transverse Millimeters (Inches) from Bottom of Liner				
	57(2.25)	159(6.25)	210(8.25)	248(9.75)	267(10.50)
Before	146.106(5.7522)	146.111(5.7524)	146.101(5.7520)	146.083(5.7513)	146.050(5.7500)
After	146.114(5.7525)	146.103(5.7521)	146.093(5.7517)	146.070(5.7508)	145.992(5.7477)
Change	0.008(0.0003)	-0.008(-0.0003)	-0.008(-0.0003)	-0.013(-0.0005)	-0.058(-0.0023)

Average Cylinder Liner ID Change: -0.020 mm (-0.0008 in.)

Piston Skirt OD, Millimeters (Inches)

	13 mm(0.5 in.) from bottom	25 mm (1 in.) from top
Before	145.847(5.7420)	145.796(5.7400)
After	145.811(5.7406)	145.766(4.7388)
Change	0.036(0.0014)	0.030(0.0012)

Average Piston Skirt OD Change: 0.033 mm(0.0013 in.)

Piston Ring End Gap, Millimeters (Inches)

	Top	No. 2 Compression	No. 3 Compression	Oil
Before	1.22(0.048)	0.81(0.032)	0.76(0.030)	0.69(0.027)
After	1.30(0.051)	0.84(0.033)	0.81(0.032)	0.74(0.029)
Change	0.08(0.003)	0.03(0.001)	0.05(0.002)	0.05(0.002)

Average Piston Ring End Gap Change: 0.05 mm(0.002 in.)

TABLE P-5

CRC DIESEL RATING SYSTEM**STANDARD COMPUTATION SHEET FOR PISTON RATING**

RATER E R Lyons DATE 2-6-79
 LABORATORY TEST NUMBER 1790-3
 STAND NO. 2 ENGINE NO. CUE 1790
 FUEL FRFA (*ap water)

TEST PROCEDURE _____
 TEST HOURS 250
 TEST LABORATORY AFLRL
 LUBRICANT 6856

DEPOSIT TYPE	DEPOSIT FACTOR	GROOVES								LANDS								NO. 1 GROOVE, VOLUME %	
		NO. 1		NO. 2		NO. 3		NO. 4		NO. 1		NO. 2		NO. 3		NO. 4		PISTON WTD * RATING	
		AREA %	DEMERIT	AREA %	DEMERIT	AREA %	DEMERIT	AREA %	DEMERIT	AREA %	DEMERIT	AREA %	DEMERIT	AREA %	DEMERIT	AREA %	DEMERIT	AREA %	UNDER- CROWN
CARBON	HC	100	1.00	100	100.00					20	20.00	45	45.00						
	MHC	100	0.75																
	MC									10	2.50	30	7.50						
	LC									70	10.50								
	VLC																		
CARBON RATING		75.00		100.00						33.00		52.50							
LACQUER	BL		0.100									10	100.0						
	DBrL		0.075																
	AL		0.050																
	LAL		0.025									10	0.25						
	VLAL		0.010									5	0.05						
LACQUER RATING												1.30							
CLEAN		0				100		100						100		100		100	
ZONAL RATING																			
LOCATION FACTOR																			
WEIGHTED RATING				75.00	100.00					33.00		53.80							

*WEIGHTED TOTAL DEPOSITS

FIGURE F-1.
CUE-1790 TEST NO. 3
Fuel Code: 7225 Oil Code: 6856

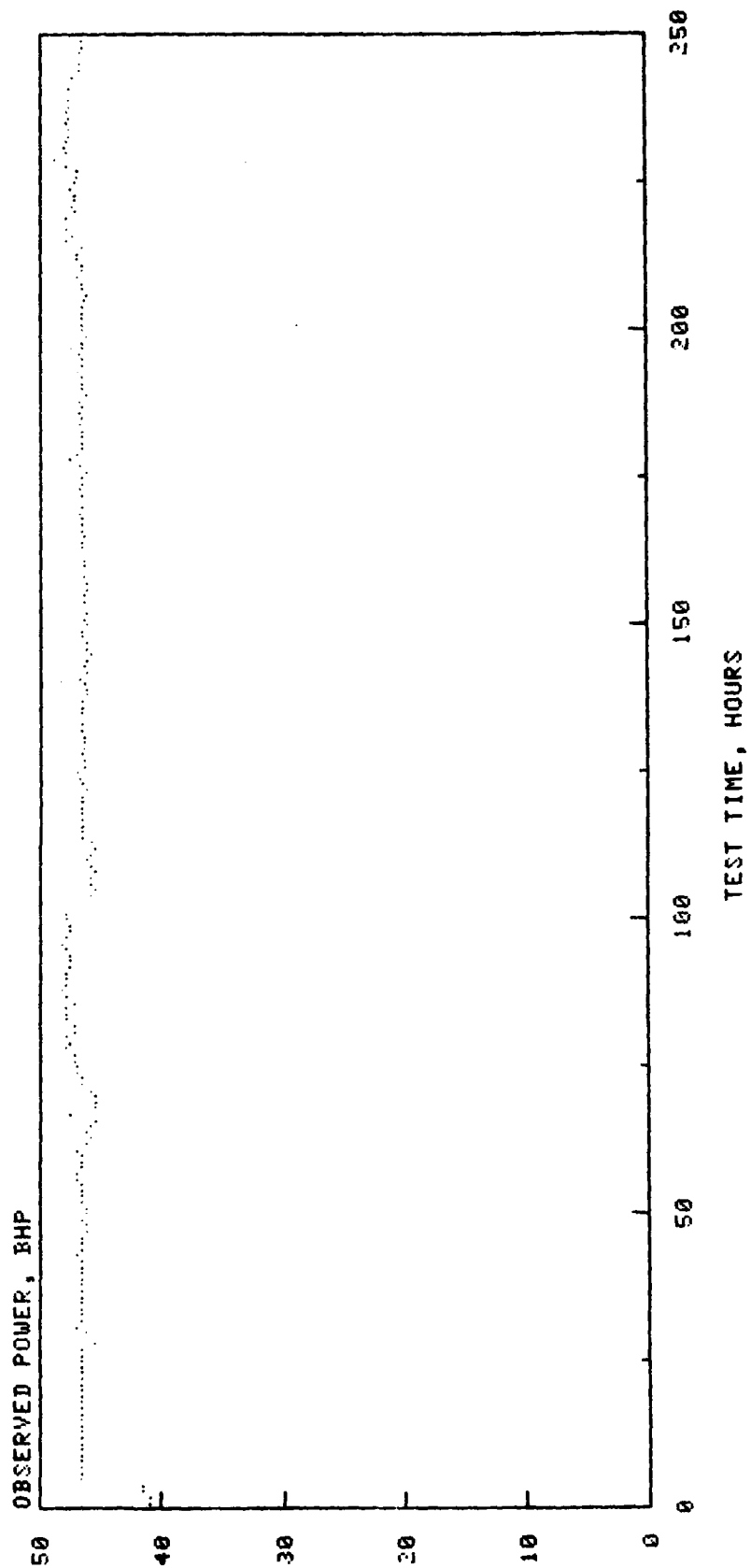
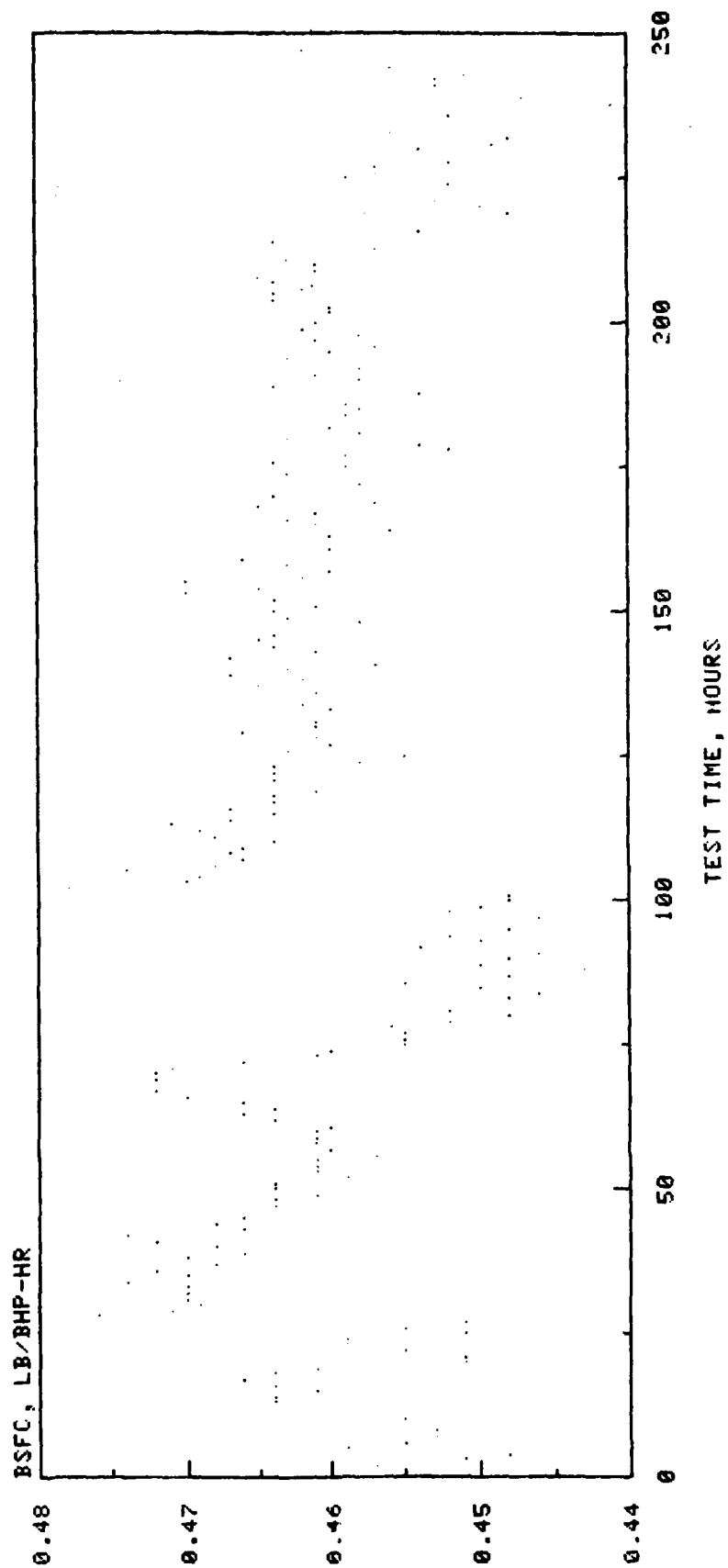


FIGURE F-2.
CUE-1790 TEST NO. 3
Fuel Code: 7225 Oil Code: 6856



Date: 6 February 1979
Fuel: FRF-A (tap water)

Test No. 1790-3

Technician: Ed Lyons
Lubricant Code: 6856

POST TEST DESCRIPTION OF ENGINE

Rings: All are free, no ringface burn. No sign of distress; oil slots all open.

Piston: Light wear pattern; looks good.

Valves: Intake face has some light pitting and has No. 8 and No. 7 lacquer deposits. Tulip has light carbon buildup. Stem has wear pattern that indicates misalignment. Exhaust face normal with 8 and 7 lacquer. Tulip has soot deposit, normal; stem normal.

Cylinder: Looks good. Very light deposits in combustion chamber. Valve seats good. Lacquer deposit uniform on cylinder.

Conrad Bearing: Normal wear on top half with light scratches.

APPENDIX G

LIST OF ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

Acronyms:

AFLRL - U.S. Army Fuels and Lubricants Research Laboratory
BRL - U.S. Army Ballistics Research Laboratory
FAA - Federal Aviation Administration
JFTOT - Jet Fuel Thermal Oxidation Tester
LOA - Letter of Agreement
MERADCOM - U.S. Army Mobility Equipment Research and Development Command
NACE - National Association of Corrosion Engineers
NARADCOM - U.S. Army Natick Research and Development Command
TARC - Total aromatic ring carbon content

Engine Abbreviations:

AVDS-1790-2C - Twelve-cylinder, air-cooled diesel engine in M60 battle tank
CLR - Cooperative Lubricants Research engine (single-cylinder laboratory engine)
CUE - Cooperative Universal Engine
CUE-1790 - Cooperative Universal Engine with AVDS-1790-2C cylinder assembly
DD3-53 - Three-cylinder, two-stroke cycle diesel engine
DD6V-53T - Six-cylinder, two-stroke cycle (V6) diesel engine
LD-465 - Six-cylinder, four-stroke cycle multifuel diesel engine

Vehicle Abbreviations:

M60 - M60 Main Battle Tank
M113A - M113A Armored Personnel Carrier

Engine Performance Abbreviations and Definitions:

CA - Crank angle
CID - Cubic inch displacement
BHP - Brake horsepower
IHP - Indicated horsepower
BMEP - Brake mean effective pressure
IMEP - Indicated mean effective pressure
BSDC - Brake specific consumption of diesel fuel portion of hybrid fuel, lb/Bhp-hr
ISDC - Indicated specific consumption of diesel fuel portion of hybrid fuel, lb/Bhp-hr
BSEC - Brake specific consumption of the fuel's net energy-of-combustion
ISEC - Indicated brake specific consumption of the fuel's net energy-of-combustion, Btu/ihp-hr
BSFC - Brake specific fuel consumption, lb/Bhp-hr
ISFC - Indicated brake specific fuel consumption, lb/ihp-hr
BSVC - Brake specific volumetric fuel consumption, gal./Bhp-hr
ISVC - Indicated brake specific volumetric fuel consumption, gal./ihp-hr

Solvent Abbreviations:

C₉+ Aromatics - Concentrate of aromatic hydrocarbons containing nine or more carbon atoms per molecule
LPA - Low aromatic content hydrocarbon solvent

Antimist Agent Codes:

AM-1 to AM-16 - AFLRL codes for candidate antimist agents
FM-9 - Antimist agent candidate under investigation by FAA

Fuel Abbreviations:

FRF - Fire-resistant fuel
FRF-A - Fire-resistant diesel fuel containing 10 vol% water and 6 vol% surfactant
FRF-B - Fire-resistant diesel fuel containing 5 vol% water, 3 vol% surfactant, and 0.2 wt% AM-1 antimist agent

Ballistics Abbreviations and Definitions:

Mann Rifle - Rigid-mounted test barrel and breech for 20-mm HEIT
20-mm HEIT - 20-mm high-explosive incendiary tracer round

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